VOL. 61 NO. 4

JOURNAL

of the

AMERICAN SOCIETY

of

NAVAL ENGINEERS, Inc.

NOVEMBER 1949

PUBLISHED QUARTERLY BY THE SOCIETY TO FURTHER
THE ADVANCEMENT OF NAVAL ENGINEERING.

PRESIDENTS OF THE SOCIETY

Current:

Rear Admiral T. A. Solberg, U. S. Navy

Past Presidents:

1889-90 Chief Engineer Nathan P. Towne, U. S. Navy
1891 Past Assistant Engineer G. W. Baird, U. S. Navy
1892 Chief Engineer David Smith, U. S. Navy
1893-94 Chief Engineer H. Webster, U. S. Navy
1895 Chief Engineer James H. Perry, U. S. Navy
1896 Chief Engineer E. D. Robie, U. S. Navy
1897 Chief Engineer David Smith, U. S. Navy
1898-99 Chief Engineer H. Webster, U. S. Navy
1900 Commander H. Webster, U. S. Navy
1901-02 Commander C. W. Rae, U. S. Navy
1903 Lieutenant Commander W. M. Parks, U. S. Navy
1904 Rear Admiral John D. Ford, U. S. Navy
1905 Commander A. F. Dixon, U. S. Navy
1906 Commander A. B. Canaga, U. S. Navy
1907 Commander B. C. Bryan, U. S. Navy
1908 Commander R. S. Griffin, U. S. Navy
1909 Rear Admiral John K. Barton, U. S. Navy
1910-11 Engineer-in-Chief H. I. Cone, U. S. Navy
1912-13 Captain R. S. Griffin, U. S. Navy
1914 Rear Admiral J. R. Edwards, U. S. Navy
1915 Captain S. S. Robison, U. S. Navy
1916 Captain C. W. Dyson, U. S. Navy
1917-18 Captain H. P. Norton, U. S. Navy
1919 Rear Admiral H. P. Norton, U. S. Navy
1920 Rear Admiral C. W. Dyson, U. S. Navy
1921 Captain A. J. Hepburn, U. S. Navy
1922 Rear Admiral C. W. Dyson, U. S. Navy
1923-24 Captain J. T. Tompkins, U. S. Navy
1925 Rear Admiral C. F. Hughes, U. S. Navy
1926 Rear Admiral M. M. Taylor, U. S. Navy
1927 Rear Admiral John Halligan, U. S. Navy
1928 Captain E. L. Bennett, U. S. Navy
1929-30 Rear Admiral H. E. Yarnell, U. S. Navy
1931 Rear Admiral S. M. Robinson, U. S. Navy
1932 Rear Admiral F. B. Upham, U. S. Navy
1933 Rear Admiral Wm. A. Moffett, U. S. Navy
1933 Rear Admiral E. J. King, U. S. Navy
1934-36 Rear Admiral William H. Standley, U. S. Navy
1937 Rear Admiral Alfred W. Johnson, U. S. Navy
1938 Rear Admiral Harold G. Bowen, U. S. Navy
1939 Rear Admiral S. M. Robinson, U. S. Navy
1940 Rear Admiral Henry Williams, U. S. Navy
1941 Captain Claud A. Jones, U. S. Navy
1942 Rear Admiral Herbert S. Howard, U. S. Navy
1943 Rear Admiral J. J. Broshek, U. S. Navy
1944 Rear Admiral C. L. Brand, U. S. Navy
1945 Rear Admiral E. W. Mills, U. S. Navy
1946 Rear Admiral Harvey F. Johnson, U.S.C.G.
1947 Rear Admiral C. W. Styer, U.S.N.
1948 Rear Admiral Roger W. Paine, U. S. Navy
1948 Rear Admiral Harvey F. Johnson, U.S.C.G., Ret.

JOURNAL

OF

The American Society of Naval Engineers, Inc.

PUBLISHED QUARTERLY

UNDER THE SUPERVISION OF THE COUNCIL:

Rear Admiral T. A. Solberg, U.S.N.

Captain Homer Ambrose, U.S.N.

Captain T. T. Dantzler, U.S.N.

Mr. M. Douglas Gibson, Jr.

Captain P. D. Gold, U.S.N.

Captain G. F. Hicks, U.S.C.G.

Rear Admiral T. C. Lonnquest, U.S.N.

Captain W. N. Mansfield, U.S.N.R.

Commander Nicholas Tiedeman, U.S.N.R.

Mr. R. M. Wilson

Captain J. E. Hamilton, U.S.N., Secretary-Treasurer

SIXTY-FIRST YEAR

Vol. 61 November 1949 No. 4

Published Quarterly at the Navy Department, Washington, D. C., by The American Society of Naval Engineers, Inc.

Entered as Second Class Matter at the Post Office at Washington, D. C. Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 3, 1918.

Subscription Rates for Non-Members.

The subscription price of the JOURNAL, postpaid to points in the United States and possessions, is $6.00. Single copies, $1.50. To other countries, $6.40. Single copies, $1.60. Beginning with the next (the February 1950) issue the subscription price for delivery in the United States will be $9.00 and for delivery outside the United States $10.00. Single copies $2.25. To other countries $2.50. All subscriptions payable in advance.

Make checks, drafts and postal money orders payable to THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

Advertising rates will be furnished on application.

Addresses will be changed at any time, but only upon notification. Immediate notice should be given of any delay in the receipt of the JOURNAL.

Address all communications for the Society to

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.
Bureau of Ships, Navy Department
Washington, D. C.

The American Society of Naval Engineers, Inc., has no official connection with the Navy Department.

TABLE OF CONTENTS

PAGE

SECRETARY'S NOTES 779

PART ONE.

Articles which have been accepted from the author for original publication.

AIRCRAFT GAS TURBINES.
ROBERT L. WELLS 785

NAVAL PROCUREMENT.
CAPTAIN JOHN H. KEATLEY, U.S.N. 799

EXAMINATION OF SURFACES.
JOHN W. SAWYER 819

ROTARY GAS TURBINE COMPRESSORS.
IRWIN E. JACKSON, JR. 829

MANAGEMENT ENGINEERING.
REAR ADMIRAL MILTON CARLSON, U.S.N. RET. 837

ION EXCHANGERS.
HARRY FLEISHER 845

THE U. S. NAVY PLASTIC BOAT PROGRAM.
COMMANDER A. C. BUSHEY, JR., U.S.N.R. 865

THE METHOD OF RESEARCH.
DAVID B. HERTZ 869

LONGITUDINAL VIBRATION.
C. S. L. ROBINSON 883

PART TWO.

Articles of value to the Society which have been published and which are republished herein with permission of and acknowledgment to the original publisher.

SURFACE TREATMENT OF DIESEL ENGINE PARTS.
Motorship, October, 1949 887

MECHANISM OF CREEP IN METALS.
Journal of the Institute of Metals, April, 1949 892

PAGE

TITANIUM ALLOYS FOR AIRCRAFT.
Aero Digest, August, 1949 908

DIESEL ENGINES AND THEIR FUELS.
British Motor Ship, October, 1948 914

METALLIZING IN RELATION TO MARINE ENGINEERING.
Transactions of the Institute of Marine Engineers,
Vol. LX, No. 12 (1948) 923

HEAT-RESISTANT ALLOYS FOR AVIATION.
Aero Digest, August, 1949 952

THE OPPOSED PISTON DIESEL ENGINE.
Pacific Marine Review, March, 1949 958

THE EFFECT OF PHASE ERRORS IN TIME-BASE INDICATOR DIAGRAMS.
Engineering, July 22, 1949 967

DEPARTMENTS.

BOOK REVIEW 975

CHANGES IN MEMBERSHIP 976

ASSOCIATION NOTES 981

Editor: Captain J. E. HAMILTON, U.S.N.

Assistant Editor: Commander FRANK C. JONES, U.S.N.

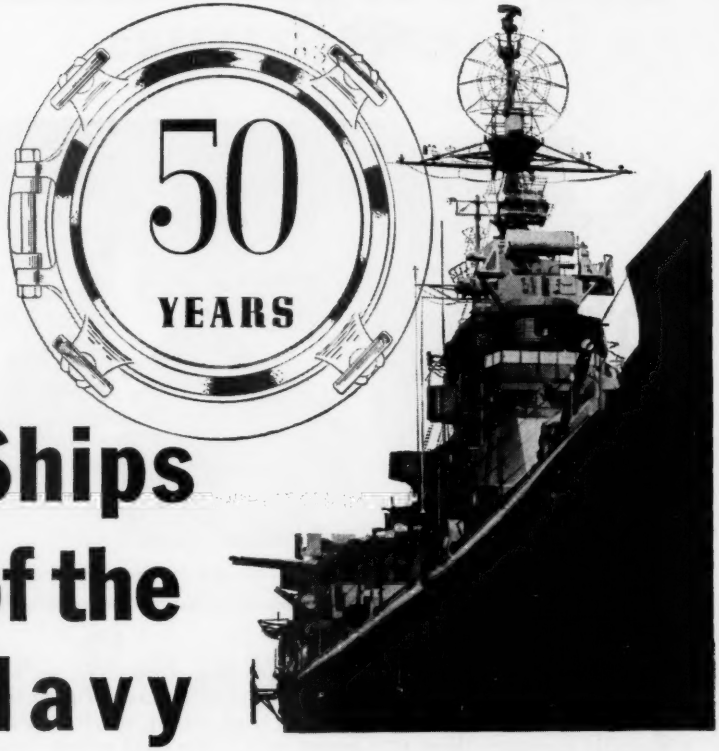
Clerk: Mr. A. G. FESSENDEN

INDEX TO ADVERTISERS

Name.	Manufacturers of or dealers in	Post office address.	Page
A			
Allis-Chalmers Mfg. Co.	Ship Propulsion and other Equipment for Marine Use	Milwaukee, Wis.	xxxi
American Brass Co.	Engineering Service on Anaconda Metals	Waterbury, Conn.	xxxiii
B			
Babcock & Wilcox Co.	Marine Water-Tube Boilers, Superheaters, Airheaters, Economizers, Oil Burners, Refractories, Seamless and Welded Tubing	85 Liberty St., New York	xiv
Bath Iron Works	Shipbuilders and Engineers	Bath, Me.	xviii
Bendix Aviation Corp.	Bendix Depth Recorder	North Hollywood, Calif.	iv
Berwind-White Coal Mining Co., The	Eureka Bituminous Steam Coal	1 Broadway, New York 4, N. Y.	xxxiii
Bethlehem Steel Co.: Shipbuilding Division	Steam Turbines, Marine Boilers, Oil Burning Equipment, Shipbuilders and Repairers	25 Broadway, New York, N. Y.	xxxiv
C			
Cleveland Diesel Engine Division, General Motors Corp.	Diesel Engines	Cleveland, Ohio	xvii
Collins Radio Company	Designers and manufacturers of radio communication and navigation equipment for the Armed Services	Cedar Rapids, Iowa	xxxi
Commercial Engineering Co., Inc.	Motors and Control for Turret Equipment for Scout Cruisers	1627 K St., N. W., Washington, D. C.	iv
Cooper-Bessemer Corp., The	Marine Diesel Engines	25 West 43rd St., New York City	xxx
Combustion Engineering Co.	Marine Steam Generators, Bent Tube and Straight Tube Boilers, Forced-Circulation Boilers, Superheaters, Economizers and Air Heaters	200 Madison Ave., New York, N. Y.	xi
Continental Rubber Works	Rubber "Socks"	Erie, Pa.	xxiv
Crane Co.	Crane Valves	836 S. Michigan Ave., Chicago, Ill.	ii
Cutler-Hammer, Inc.	Electric Control Apparatus	1354 St. Paul Ave. Milwaukee, Wis.	xxii
D			
De Laval Steam Turbine Co	Steam Turbines	485 Nottingham Way, Trenton, N. J.	vi
Diamond Power Specialty Corp.	Diamond Soot Blowers	Detroit, Mich.	xv
E			
Electric Boat Co.	Better Submarines for Greater Security	445 Park Avenue, New York 22, N. Y.	xxx
Electric Storage Battery Co.	Exide Batteries	Allegheny Ave. and 19th St., Philadelphia, Pa.	viii
Elliott Co.	Elliott Motors, Generators, Steam and Gas Turbines, Condensers, Deaerating Feedwater Heaters, Turbo Chargers, Strainers, Tube Cleaners, etc.	Jeanette, Pa.	iv

Name.	Manufacturers of or dealers in	Post office address.	Page
F			
Farrel-Birmingham Co., Inc.	Farrel Propulsion Gears	344 Vulcan St., Buffalo 7, N. Y.	xii
Fairbanks-Morse	Diesel Engines	Chicago, Ill.	xx
Foster Wheeler Corp.	Marine Steam Generators, Condensers, Bent Tube and Straight Tube Boilers, Superheaters, Water Walls, Economizers, Air Heaters, Feed Water Heaters, Evaporators, Condenser Tubes, Pumps, Waste Heat Boilers, Vacuum Refrigeration Systems.	165 Broadway, New York	xxi
G			
General Electric	Electric Machinery of All Classes	Schenectady, N. Y.	xxiii
Gibbs & Cox, Inc.	Naval Architects and Engineers	New York, N. Y.	xxxii
Griscom-Russell Co.	Distilling Plants, Feed Water Heaters	285 Madison Ave., New York	xxxii
H			
Hydraulic Power Division The Hydraulic Press Mfg. Co.	Hydraulic Machinery	3011 Marion Rd. Mount Gilead, Ohio, U.S.A.	x
I			
Ingersoll-Rand	All Types of Pumps, Condensers, Ejectors, Compresors, etc.	11 Broadway, New York, N. Y.	xxii
International Nickel Co.	Producers of Nickel	67 Wall St., New York, N. Y.	v
International Telephone and Telegraph Corp.	Communications — Research — Manufacturing	67 Broad St., New York, N. Y.	xxvii
J			
Johns-Manville	Insulation, Refractory Cements, Packings, Brake Linings, Asbestos Ebony for Switch and Panel Boards, Waterproofing, Transite Asbestos Sheets, Transite Pipe, Roofing and Shingles, Flooring, Insulating Board Products	22 East 40th St., New York City	viii
K			
Kearfott Engineering Co., Inc.	Windows	117 Liberty St., New York	xxviii
Kingsbury Machine Works, Inc.	Thrust Bearings, Journal Bearings, Thrust Meters	Frankford, Philadelphia, Pa.	xxix
L			
Lanman Engraving Co.	Photo Engravers	612 L St., N. W., Washington, D. C.	xv
M			
Moffitt, Lucian Q., Inc.	Cutless Bearings for Stern Tubes and Struts	Akron, O.	iii

Name.	Manufacturers of or dealers in	Post office address.	Page
N			
Newport News Shipbuilding & Drydock Co.	Naval and Merchant Vessels	Newport News, Va.	ix
New York Shipbuilding Corporation	Shipbuilders	Camden, N. J.	i
O			
Okonite, Co., The	Insulated Wires and Cables	Executive Office, Passaic, N. J.	xxvi
R			
Radio Corporation of America: Govt. Equip. Section	Radio Equipment	Camden, N. J.	xviii
Rockbestos Products Corp.	Flame Proof Insulated Wires and Cables	New Haven, Conn.	xxxi
S			
Seaporcel Metals, Inc.	Ceramic Coated Products	28-20 Borden Avenue, Long Island City, N. Y.	iii
Sperry Gyroscope Co., Inc.	Radar, Loran, Gyro-Pilots, Gyro-Compasses, Electric and Hydraulic Steering Equipments, Magnetic Compass Pilot, Rudder Angle Indicator, Naval Fire Control Instruments, Aircraft Gyropilots, Flight Instruments	Great Neck, N. Y.	vii
T			
Terry Steam Turbine Co.	Steam Turbines	Hartford, Conn.	xxviii
Timken Roller Bearing Co.	Timken Tapered Roller Bearings	Canton, Ohio	xiii
U			
U. S. Naval Institute	U. S. Naval Institute Proceedings	Annapolis, Md.	xxv
W			
Ward Leonard Electric Co.	Electric Control Devices	Mount Vernon, New York	xxxi
Westinghouse Electric & Mfg. Co.	Marine Steam and Electrical Equipment	East Pittsburgh, Pa.	xvi
Worthington Pump & Machinery Corp.	Pumps, Condensing Apparatus, Diesel Oil Engines, Gas Engines, Fluid Meters, Compressors, Feed Water Heaters	Harrison, N. J.	xix



Ships of the Navy

...Ahead of Schedule

Never before World War II has Industry performed such feats of production . . . a record that created the greatest Navy of all time.

The achievements of New York Ship in this program were equally outstanding. From January 1, 1940, the Yard developed complete designs for seven classes of major combatant ships, twenty-nine of which were built at the Yard and delivered eight to thirteen months ahead of contract dates.

NEW YORK SHIPBUILDING CORPORATION

CAMDEN, NEW JERSEY

traffic cops

...ABOARD SHIP

These "traffic cops" on Navy's ships keep steam, water, oil, air and other vital fluids moving in the right direction. In case of pipe line breaks, they automatically stop backflow; keep piping services intact.

Unusually compact, these 600-pound cast C-Mo steel swing check valves were designed exclusively for Navy by Crane. They're the regrinding type, with a tilted, bolted cap providing easy access for servicing.

Ever since Navy took to steam, Navy and Crane engineers have partnered in developing all types of piping equipment for severest sea duty. However exacting the specifications, Crane can match them with experience, manpower, and machinery found only in the world's largest valve and fitting manufacturing plant.

CRANE CO., *General Offices:* 836 S. Michigan Ave., Chicago 5, Ill.
Branches and Wholesalers Serving All Industrial Areas

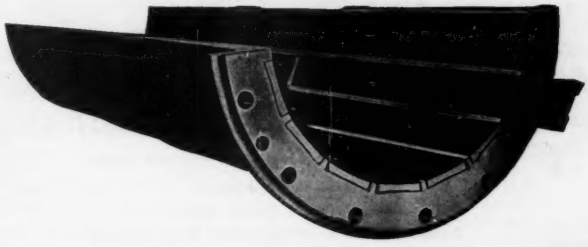
VALVES • FITTINGS • PIPE • PLUMBING • HEATING

Everything from **CRANE** *for Marine Piping Systems*

CUTLESS BEARINGS

for

Stern Tubes and Struts



Soft rubber bearing surface—efficiently lubricated by water—this bearing far outlasts all hard surface types, protects propeller shafts, reduces vibration. More than pays for itself in extra wear alone. Saves you time, trouble, and upkeep expense. Write for 60-page booklet.

LUCIAN Q. MOFFITT, INC.

AKRON, OHIO

Seaporcel

REG. TR. MARK

is a ceramic coating (fused into its metal base at 1550° F.)

SEAPORCEL increases life of mufflers, tail pieces, incinerator uptakes and other parts of ships where corrosion, erosion and thermal shock are factors.

SEAPORCEL METALS, INC.

28-20 Borden Avenue

Long Island City New York

ELLIOTT POWER EQUIPMENT

serves the fleet and Naval bases with such equipment as —

Motors • Generators
Deaerating Feedwater Heaters
Turbine-Generators • Mechanical Drive Turbines
Condensers • Strainers • Tube Cleaners

Information and bulletins on request Q-1075a

ELLIOTT COMPANY JEANNETTE PA.
District Offices in Principal Cities

Bendix DEPTH RECORDER

The Bendix Supersonic Depth Recorder draws an instantaneous, permanent chart of all undercraft conditions *in their natural profile* as you pass over them. Weighs only 90 pounds. Easily installed in any convenient location. Accurate to 200 feet or 200 fathoms. Write for complete details.

Pacific Division
Bendix Aviation Corporation
NORTH HOLLYWOOD, CALIF.

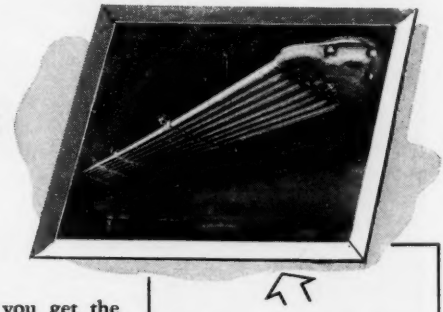
CONTRACTORS TO THE U. S. NAVY

COMMERCIAL ENGINEERING COMPANY

COMPLETE LINE ELECTRICAL, MECHANICAL AND MARINE EQUIPMENT

1627 K St., N. W. National 9238 Washington, D. C.

Two Outboard Cooling Systems that cut operating costs



"Closed" cooling systems help you get the most in service and economy from engines, especially where cruising waters are salt, debris-infested, or sandy.

But . . . unless your cooling system is adequately rustproof and corrosion-resistant, it can cause more trouble than it cures!

A good way to insure your closed outboard cooling system against expensive corrosion failures and rust fouling is to specify *Monel** tubing for under-water heat exchangers and inboard piping. For, in addition to being 100% rustproof and highly resistant to salt-water corrosion, Monel is *actually stronger than structural steel*...extra protection against under-water damage. Monel is galvanically neutral to the bronze through-hull fittings and return bends.

If you are considering the many advantages of fresh-water cooling for your own boats, remember this . . . a single lay-up for repairs may cost a great deal more than the small additional expense of dependable *Monel* protection.

Your local shipyard or boat builder will be glad to quote on rustproof *Monel* tubing for keel coolers; also Monel propeller shafts, fittings, and accessories. Why not investigate . . . soon?

THE INTERNATIONAL NICKEL COMPANY, INC.
67 Wall Street, New York 5, N. Y.

*Monel** *"It's the SEAGOIN'* metal"*
*Reg. U. S. Pat. Off.

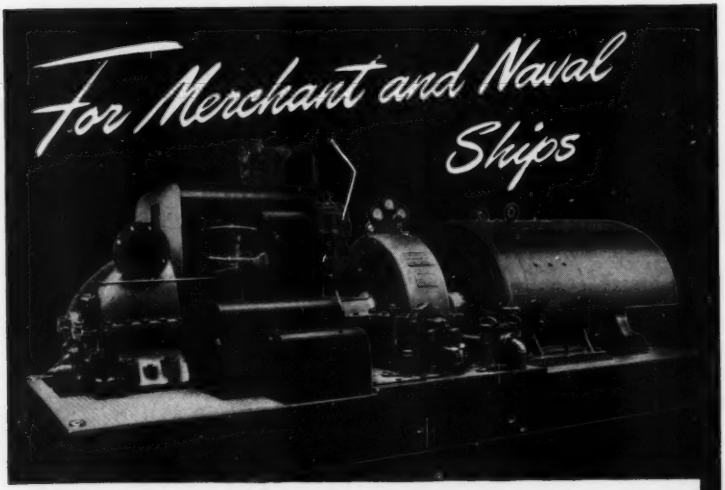
Keel condenser of a Walter Clean-Flo Cooler, installed on the fishing boat, Ventura, *of City Island, N. Y., owned by Capt. Sol Newman and partners. The tubing is strong, light-walled seamless Monel (1¼ in. O.D. with 0.065 in. wall). Fittings are cast bronze, secured to the wood hull with Monel bolts, nuts, and "K"* Monel lock washers.* Ventura's *Monel propeller shaft has been in service for the past ten years. Her planks have been refastened with Anchorfast nails of Monel, driven between the old rusted galvanized fastenings*

Walter Clean-Flo Coolers made by G. WALTER MACHINE CO., *84 Cambridge Ave., Jersey City 7, N. J.*

• • •

A Monel-tubed keel condenser installed on the 45-ft. tug, Charles E. Gray, *of Brunswick, Ga. Return bend and through-hull connection are bronze. The* Charles E. Gray *is also equipped with a rustproof, corrosion-resistant Monel propeller shaft, and Monel hull fastenings.*

Cooling system fabricated from standard I.P.S. Monel pipe, and installed by BRUNSWICK MARINE CONSTRUCTION CORP., *Brunswick, Georgia.*



DE LAVAL GENERATING SETS

The reliability and efficiency of De Laval marine turbo-generating sets has been demonstrated conclusively by the hundreds of units furnished for ships of the Merchant Marine and Navy. De Laval turbo-generating sets are distinguished by their neat compact design, accessibility of all parts, simplified governor control, automatic nozzle control and other features contributing to reliability, efficiency and smooth operation.

Sales Offices

ATLANTA - BOSTON - CHARLOTTE - CHICAGO
CLEVELAND - DENVER - DETROIT - DULUTH
EDMONTON - GREAT FALLS - HAVANA - HELENA
HOUSTON - KANSAS CITY - LOS ANGELES - MONTREAL - NEW ORLEANS - NEW YORK - PHILADELPHIA - PITTSBURGH - ROCHESTER - ST. PAUL
SALT LAKE CITY - SAN FRANCISCO - SEATTLE
TORONTO - TULSA - VANCOUVER - WASHINGTON, D. C. - WINNIPEG

N-3

DE LAVAL

TURBINES • HELICAL GEARS • WORM GEAR SPEED REDUCERS • CENTRIFUGAL PUMPS • CENTRIFUGAL BLOWERS AND COMPRESSORS • IMO OIL PUMPS

DE LAVAL STEAM TURBINE COMPANY **TRENTON 2, NEW JERSEY**

FOR *Land*...

OR *Sea*...

OR *Air*...

precision instruments

and controls from

precision research and

engineering for the

Army, Navy and Air Force

Sperry Gyroscope Company

DIVISION OF THE SPERRY CORPORATION

GREAT NECK, NEW YORK

Exide

1888 1949

DEPENDABLE . . . in every
storage battery application—
on land, at sea, and in the air.

THE ELECTRIC STORAGE BATTERY COMPANY
PHILADELPHIA

Johns-Manville

Materials for
MARINE SERVICE

Incombustible Joiner Materials • Acoustical Materials
Asbestos Ebony for Switch and Panel Boards
Structural Insulations • Boiler and Engine Room Insulations
Packings • Gaskets

For complete details, write to
Johns-Manville
Box 290, New York 16, N.Y.

JOHNS-MANVILLE JM PRODUCTS

1891 - 1949

FIFTY-EIGHT YEARS OF SERVICE

NEWPORT NEWS Hulls No. 1 and 2 built in 1891 are shown on September 28, 1949, in the waters of their birth, Hampton Roads. After fifty-eight years of service both vessels are still working daily. Hull No. 1, formerly the DOROTHY, is now the J. ALVAH CLARK of the Wood Towing Corporation. Hull No. 2, formerly EL TORO, is now the VIRGINIA of the Norfolk Dredging Company.

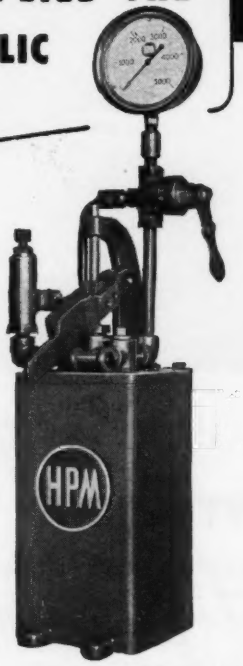
These two vessels are further operating evidence of the fulfilment of the policy established by the Newport News Founder, Collis P. Huntington: "We shall build good ships here at a profit if we can at a loss if we must, but always good ships."

NEWPORT NEWS SHIPBUILDING AND DRY DOCK COMPANY

NEWPORT NEWS, VIRGINIA

For 30 Years...

H-P-M HAS SUPPLIED THE NAVY THIS HYDRAULIC HAND PUMP!



These pumps are designed to give dependable, long life service in testing all types of boilers, pressure vessels and high pressure pipe lines. They are complete with reservoir and use either water or oil as a pressure medium. Also included with each unit are safety valve, operating valve and pressure gauge.

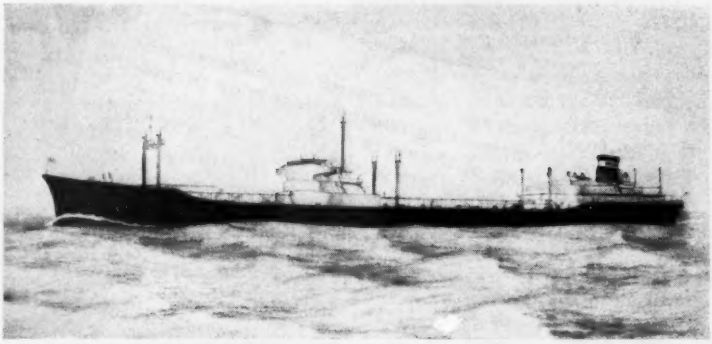
These pumps are available for immediate delivery. Check size listed below. Write today for complete specifications.

HYDRAULIC POWER DIVISION
THE HYDRAULIC PRESS MFG. CO.
3011 Marion Road Mount Gilead, Ohio, U.S.A.

Maximum Pressure psig	GPM @ 50 Strokes/Minute	Disp. per Stroke Cubic Inches	Plunger Diameter
10,000	.07	.324	11/32"
5,000	.13	.604	15/32"
4,500	.14	.687	1/2"
3,000	.23	1.073	5/8"
2,100	.33	1.546	3/4"
1,500	.45	2.104	7/8"
1,200	.59	2.748	1"

HYDRAULIC HPM MACHINERY
SINCE 1877
PRESSES · PUMPS · VALVES · FLUID MOTORS · POWER UNITS

C-E Boilers power new 30,000-ton tankers



Artist's profile view showing one of the three new super-tankers now under construction for Philadelphia Tankers, Inc.

In April, May and June of this year keels were laid at the Camden yard of the New York Shipbuilding Corp. for three new 30,000-ton super tankers for Philadelphia Tankers, Inc.

These new ships, among the largest now under construction, will be 660′ overall with 85′ beam and have a draft of 34′ when carrying a full deadweight load of 30,000 tons. They are designed for a cargo capacity of 357,000 barrels and a service speed of 17 knots.

C-E Sectional Header Boilers will power this notable new tanker fleet. There will be two boilers of 65,000 lb of steam per hour each, normal capacity, on each ship. B-334A

COMBUSTION ENGINEERING—SUPERHEATER, Inc.

A Merger of COMBUSTION ENGINEERING COMPANY, INC. and THE SUPERHEATER COMPANY

200 Madison Avenue, New York 16, N. Y.

All Types of Steam Generating, Fuel Burning and Related Equipment for Stationary and Marine Applications

WORKING WITH THE NAVY

Since 1934

Fifteen years ago Farrel started an intensive program of engineering research to develop propulsion gearing of the types required by the Navy. Since then the designs produced have been proved at sea in over 1200 ships of more than thirty different types.

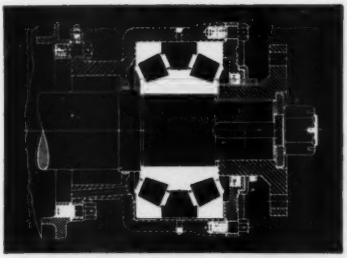
All gears are generated by the famous Farrel-Sykes process. Their accuracy of tooth contour and tooth division and their continuity of tooth engagement result in smooth, quiet operation, even at high speeds.

FARREL-BIRMINGHAM COMPANY, INC.

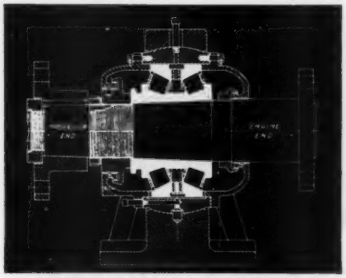
Marine Division

3700 Chrysler Building, New York 17, N. Y.

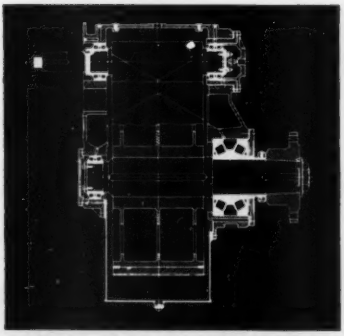
HOW TO KEEP PROPELLER THRUST IN ITS PLACE



Timken propeller thrust bearing mounted on an extension of the engine crankshaft and bolted to the engine case.



Timken bearing separate thrust block for use between engine and propeller shaft.



Single reduction herringbone gear drive with Timken thrust bearing mounted on propeller end of main shaft.

It's not difficult to stop propeller thrust — if you don't care how much friction it takes. But that's not for this day. Now, thrust can be kept in its place with minimum friction, minimum loss of power, minimum wear and without lubrication difficulties.

It's done with rollers — Timken tapered rollers operating in Timken tapered races, providing maximum propeller thrust capacity and smoothness of operation under all water and weather conditions.

Timken marine thrust bearings can be built into the propulsion units, used in the form of separate thrust blocks; or incorporated in marine gear drives. Consult your ship builder or our engineers.

THE TIMKEN ROLLER BEARING COMPANY, CANTON 6, OHIO
Cable Address "TIMROSCO"

Smoothing the Path of Progress for 50 Years

TIMKEN
TRADE-MARK REG. U. S. PAT. OFF.
TAPERED ROLLER BEARINGS

FARRELL LINES' FINEST

. . . POWERED BY B&W BOILERS

Picturesque transportation in Durban, a Farrell Lines' South African port-of-call.

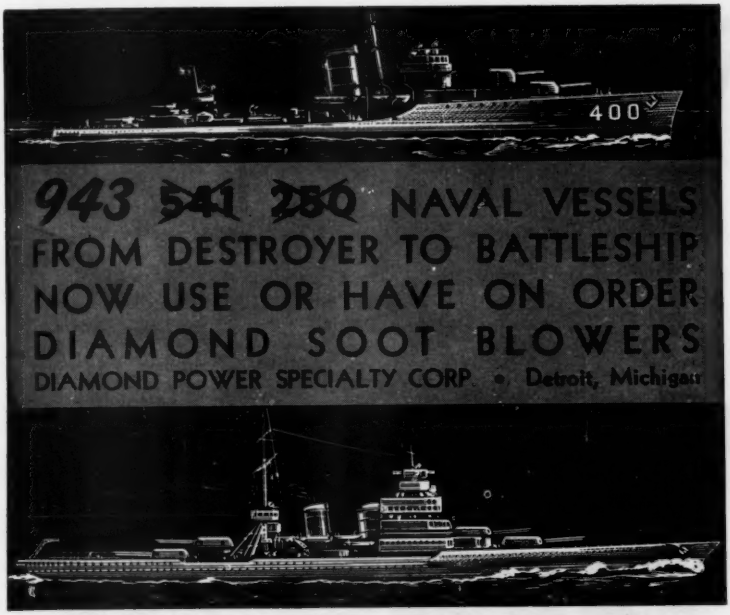
AFRICAN ENTERPRISE and AFRICAN ENDEAVOR, Farrell Lines' newest and finest sister ships, now provide more luxurious comfort than ever before between New York and South African ports. And once again B&W Marine Boilers contribute importantly to maintaining a shipping company's reputation for swift, dependable service.

Supplying boilers for ships that mark progress is a 70-year-old story with B&W. Whatever the extent of your operation—lake, river, or ocean service; whether your problem is powering new ships or reboilering old ones—the B&W Marine Department can help you to profitable realization of your steam-generating requirements.

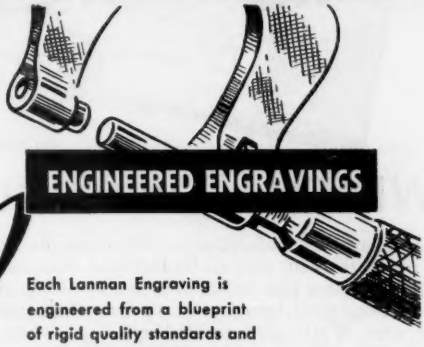
BABCOCK & WILCOX

THE BABCOCK & WILCOX CO.
GENERAL OFFICES: 85 LIBERTY ST., NEW YORK 6, N. Y.
WORKS: ALLIANCE AND BARBERTON, O.; AUGUSTA, GA.

M-257


400
943 541 250 NAVAL VESSELS
FROM DESTROYER TO BATTLESHIP
NOW USE OR HAVE ON ORDER
DIAMOND SOOT BLOWERS
DIAMOND POWER SPECIALTY CORP. • Detroit, Michigan

WASHINGTON'S
OLDEST
COMMERCIAL
PHOTO-ENGRAVING
HOUSE



ENGINEERED ENGRAVINGS

Each Lanman Engraving is engineered from a blueprint of rigid quality standards and precision workmanship . . . for quality and service it's Lanman!

Lanman
ENGRAVING COMPANY
612 L STREET, N. W. WASHINGTON, D. C. EXECUTIVE 5150

YOU CAN BE **SURE**.. IF IT'S

Westinghouse

- Diesel Electric Marine Propulsion . . B-3495
- Geared-Turbine Marine Propulsion . B-3497
- Turbine-Electric Marine Propulsion . B-3308
- Passenger-Cargo Vessels B-3779

WHICH . . . WILL HELP YOU MOST?

Get complete, authoritative information—FREE. Each book is presented in a quick-to-read, easy-to-understand manner. Pages of facts, drawings and photographs, plus colorful schematic diagrams.

Choose your booklet, or all four. Ask your nearest Westinghouse office or write Westinghouse Electric Corporation, P. O. Box 868, Pittsburgh 30, Pennsylvania.

J-93450

Westinghouse

HEADQUARTERS FOR
MARINE STEAM AND ELECTRICAL EQUIPMENT

Copyright 1949, by THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

JOURNAL

OF

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

VOL. 61. NOVEMBER 1949. No. 4.

Statements contained in articles herein are the private opinions and assertions of the writers and should therefore not be construed as reflecting the views of The American Society of Naval Engineers, Inc., or of any other organization with which such writers are affiliated.

The Society as a body is not responsible for statements made by individual members

COUNCIL OF THE SOCIETY

(Under whose supervision this number is published).

Rear Admiral T. A. SOLBERG, U. S. N., President

Captain HOMER AMBROSE, U. S. N.
Captain T. T. DANTZLER, U. S. N.
Mr. M. DOUGLAS GIBSON, JR.
Captain P. D. GOLD, U. S. N.
Captain G. F. HICKS, U. S. C. G.
Rear Admiral T. C. LONNQUEST, U. S. N.
Captain W. N. MANSFIELD, U. S. N. R.
Commander NICHOLAS TIEDEMAN, U. S. N. R.
Mr. R. M. WILSON.

Captain J. E. HAMILTON, U.S.N., Secretary-Treasurer

SECRETARY'S NOTES

COUNCIL MEETING

The last Council meeting made two revolutionary decisions. Both of them are being submitted to the membership for consideration with the regular annual ballot.

First: It was decided *for the first time in 61 years* to suggest an increase in the annual dues. The Council, after full consideration, decided that an increase to $7.50 per year was the optimum figure for putting the Society's finances on a sound basis without waiting for an increase of 3 or 4 thousand members. Those who have read these notes for the last few issues are familiar with the situation.

Second, on suggestion of a group of members in San Diego, Calif., it was decided to suggest the sponsorship of local chapters. Most other technical societies have found these of value *where* the local leaders have made them so. If the members approve, the Council will promulgate governing rules.

Official Department of Defense Photo.

Banshee—Shown here is one of the U. S. Navy's twin jet engined carrier based aircraft—the McDonnell F-2H-1. It is in the 575 miles per hour class, and recently flew to the altitude of 51,000 feet and took pictures of the Nation's Capital. The *Banshee* is powered by two Westinghouse J-34 turbo-jet engines, has a wing span of over 41 feet, a length of 39 feet and is 14 and a half feet high.

FORMAT

After promising to drop the subject, it is here continued for a final appearance. This issue is an assortment of formats of several of the articles. What is being sought is the optimum condition of readability and cost. Shortly after this issue appears, decision will be reached on treatment of format for 1950. Comments, criticisms and suggestions from any source will be appreciated.

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

This Society was founded in 1888, by a group of officers of the old Engineering Corps of the Navy. Its purpose is to bind together in a non-profit, non-political, non-pressure group all of the men in the United States who are engaged or interested in Naval Engineering.

Three types of membership are offered:

NAVAL: for Naval, Coast Guard and Marine Corps commissioned and warrant officers and ex-commissioned and warrant officers.

CIVIL: for qualified civilian engineers.

ASSOCIATE: for interested civilians.

The Society publishes a JOURNAL four times a year. All members receive the JOURNAL without extra cost. The JOURNAL publishes original articles on any subject which is embraced in the currently very broad term "Naval Engineering". It also reprints articles deemed to be of value and interest from other leading engineering publications throughout the world. The original articles which are being published for the 61st continuous year frequently advance ideas which are the true forerunners of engineering developments. They are available only in the JOURNAL.

Membership in the Society cannot fail to be of material benefit to anyone who is engaged in any phase of Naval or Marine Engineering Work.

Membership is always open and any one interested who is qualified for any form of membership is urged to join.

We are convinced that the advantages of membership should be made clear to any one eligible. This represents an apparent change of policy, but is really much more than that. The last war was of such breadth in a naval technical sense that the number of individuals who became eligible for Society membership jumped into the hundreds of thousands. The pressure and rapid action of war

tures of the Nation's Capital. The *Banshee* is powered by two Westinghouse J-34 turbo-jet engines, has a wing span of over 41 feet, a length of 39 feet and is 14 and a half feet high.

prevented wide dissemination of information about the Society. We would like to make up that deficiency now as well as possible.

More important, perhaps, than the number of people who should be told about the Society and given an opportunity to join, is the tremendous growth in the scope of "Naval Engineering". Those two words are used just as they were 61 years ago. Even a young engineer knows enough engineering history to compare a naval vessel of today with one of 1888. As many fields of engineering development during this period could be listed as one wanted to devote space to. Just a few, every one of which has its definite NAVAL application, will be mentioned:

Alloy steel applications
Aluminum applications
Electricity
Electronics
Internal Combustion engines
Structures for flight
Structures for flotation
Jet engines
Nucleonics
Industrial relations

Each of the myriad fields is a branch of engineering but the naval application of every one is a part of Naval Engineering. We ourselves cannot appreciate the tremendous breadth of the thing of which we are a part.

Each of the engineering branches is represented by one or more societies. Only *our* society exists for the purpose of correlating and coordinating so many of them.

An attempt has been made to define "Naval Engineeing". Each reader can with a little thought and imagination arrive at his own definition. Each may differ in some respects, but surely all will result in justification for an American Society of Naval Engineers and for the benefits of membership to those qualified and interested.

PART ONE

ORIGINAL ARTICLES

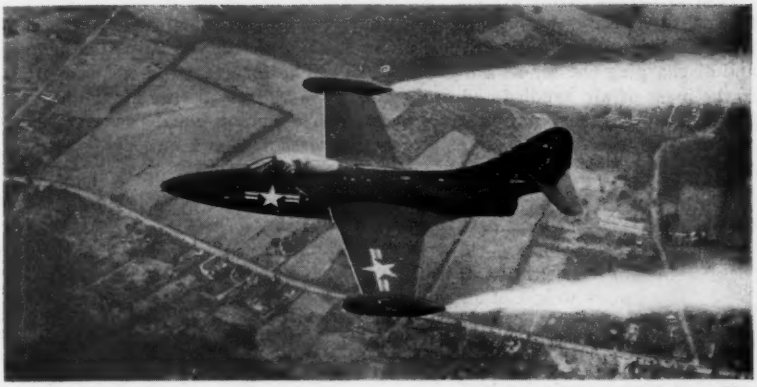
The articles which the Editor, acting under the supervision of the Council, has accepted for publication in Part One are the original works of the authors.

They are offered in furtherance of the Society's raison d'etre: to further the advancement of naval engineering. Discussion of any article is invited for publication in a subsequent issue.

Permission to reprint is freely granted on condition that *full acknowledgment is given* to the author and to the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS.

Official Photograph U. S. Navy.

CVL-49 U.S.S. *WRIGHT*—SMALL AIRCRAFT CARRIER.



Official Department of Defense Photo.

CVL-49 U.S.S. *WRIGHT*—SMALL AIRCRAFT CARRIER. *Official Photograph U. S. Navy.*

AIRCRAFT GAS TURBINES

A Review of the Considerations Which Govern Mechanical Design

ROBERT L. WELLS

THE AUTHOR

ROBERT L. WELLS graduated from the University of Rochester in 1939 with a degree in Mechanical Engineering. In 1940 he received his M.S. in Mechanical Engineering from California Institute of Technology. For four years he worked in the Mechanics Department of the Westinghouse Research Laboratories on the problem of mechanical shock. For this work he was awarded a certificate of Commendation by the United States Navy. Since 1945 he has been in the Aviation Gas Turbine Division of the Westinghouse Electric Corporation. He is now Section Engineer in charge of 24C Turbo Jet Engines.

The past decade has brought a considerable change in military aviation. One of the primary reasons for this change was the development of the turbo-jet engine and the development of aircraft designed to make best use of the characteristics of the new power plant. A discussion of some of the problems encountered during the design and development of the turbo-jet engine is the subject of this paper.

A brief review of the principle of operation of the turbo-jet engine is in order at the start of this paper. Fundamentally, the propulsive thrust of the engine is obtained by taking a quantity of air in at some velocity relative to the engine and discharging the air at a higher velocity. The forward thrust is proportional to the mass of air handled and to the change in velocity of the air while passing through the engine. For a first approximation assuming equal pressures at inlet and exhaust, the thrust is given by the expression:

$$F = \frac{w_a}{g}(v_j - v_p)$$

where

F = jet thrust in lbs.
w_a = weight of air in lbs./sec.
g = acceleration of gravity in ft/sec.^{2}
v_j = velocity of the exit air relative to the engine (jet velocity) in ft/sec.
v_p = velocity of the inlet air relative to the engine (which is the velocity of the airplane in flight) in ft/sec.

Taking into consideration the weight of fuel, w_f, added to the air the equation becomes

$$F = \frac{w_a}{g}(v_j - v_p) + \frac{w_f}{g} v_j$$

The added term accounts for less than 2% of the total. In designing jet engines, effort is always expended in obtaining as high an airflow as possible for a given engine size because the thrust is directly proportional to the weight of air handled.

The similarity between the operation of a turbo-jet engine and a propeller drive is evident when it is realized that the propeller's primary function is to accelerate a mass of air rearward in order to obtain a forward reaction on the propeller blades. The difference is in the relatively large quantity of air handled by a propeller drive and the relatively low velocity of the air leaving the propeller.

Intermediate between the turbo-jet and the conventional propeller drive is the turbo prop engine. Its thrust comes partly from air passing through the engine and emerging at a high velocity in the jet and partly from acceleration of a large mass of air by the propeller.

In order to visualize the thermodynamic process by which the turbo jet engine accelerates the mass of air and thus obtains its forward thrust attention is directed to Figure 1, a schematic longitudinal section of an axial flow turbo-jet engine. The basic components of the air flow path, in the sequence in which the air passes through them are compressor, combustion chamber, turbine, and exhaust nozzle. Figure 1 shows curves of gas pressure, temperature, and velocity for a typical condition of engine operation. The compressor, by a small pressure rise in each of the separate stages, brings the air to its maximum pressure at the

outlet end. A small pressure loss takes place as the air passes through the combustion chamber where it unites with the fuel supplied. Part of the main pressure drop occurs as the gas passes through the turbine where it gives up the energy required to drive the compressor rotor. The remaining pressure energy is used to accelerate the gas in the exhaust nozzle.

The temperature curve of Figure 1 shows a rise of around 300°F in the compressor followed by a large rise to the maximum temperature at the outlet end of the combustion chamber. Local temperatures are higher than indicated, but the curve is reasonable for average temperature.

We noted earlier that the thrust of the engine was proportional to the velocity change of the gases passing through it. The velocity curve of Figure 1 shows the large acceleration that takes place in the turbine and in the exhaust nozzle.

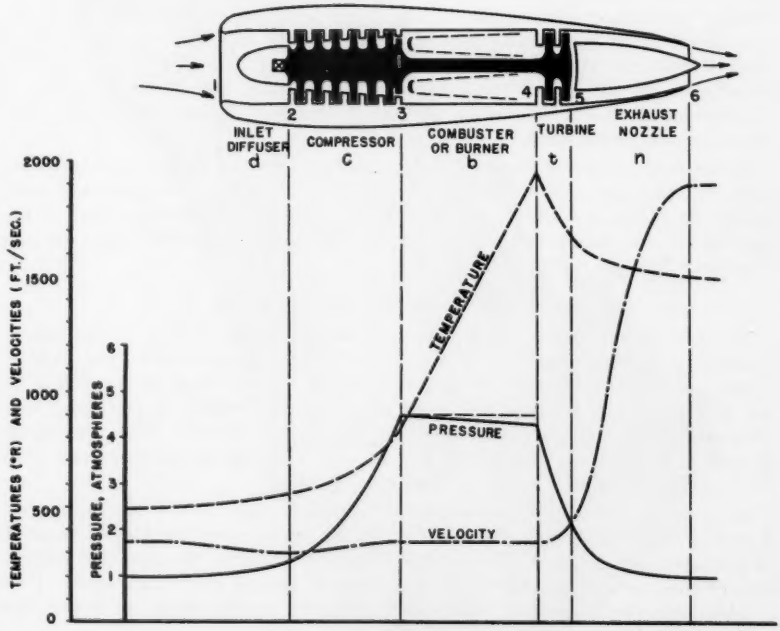


Figure 1

The cut away engine shown in Figure 2 is a turbo-jet engine developed by the Westinghouse Electric Corporation on a contract with the United States Navy Bureau of Aeronautics. It is known by both its Westinghouse designation, 24C, and its Navy-Air Force designation, J34. Currently this engine is being used in four Navy production airplanes, the McDonnell F2H, the Chance Vought F6U and F7U, and the Douglas F3D. It is also used in several experimental planes, both Navy and Air Force, including the Douglas D558-II, the McDonell XF88, and the Lockheed XF90. The J34 is the third of a series of turbo-jet engines developed cooperatively between Westinghouse and the Bureau of Aeronautics. The experience gained on the earlier models has been drawn on heavily in the design of this engine.

Many features of the mechanical construction of the J34 engine can be seen by a study of Figure 2. Air passing into the engine enters through the annular spacer between the oil cooler (1) and the dome covering the electric starter motor (2). The oil cooler is bolted to the inlet bearing support (3), a magnesium casting with four radial struts which supports the front end of the compressor rotor (4). The stationary compressor vane assemblies are retained in cast aluminum housings (5). The compressed air leaving the outlet end of the compressor passes into the diffuser section (6), and then into the combustion chamber where the burning takes place inside a double annular combustion liner (7). The products of combustion pass through the two stage turbine (8) and the exhaust collector (9) which supports an inner cone (10). The exhaust nozzle is bolted to the aft end of the exhaust collector and is not shown in Figure 2. The turbine shaft (11) transmits the power from the turbine necessary to drive the axial flow compressor.

Solutions to design problems discussed in the following part of this paper are those reached and incorporated in this engine. As with all engineering work, design decisions are always a compromise, and the factors that lead to one solution on one engine will probably not be the same on another engine or even at a later date on the same engine.

Arrangement of Components in Air Flow Path.

The factor that was given the greatest weight in the choice of the general mechanical arrangement of the air flow path was frontal area. The field of application of turbo-jet power plants is in the speed range above 500 miles per hour. When working in this range, the airplane designer can in most cases show a definite increase in top speed of a proposed airplane when the engine frontal area per pound of thrust is decreased. This is particularly true when the engines are located in the wings or wing roots.

In considering the choice between the two basic types of a compressor, axial flow and centrifugal, other factors than frontal area were considered. Analysis of available data indicated that in larger sizes particularly, the potentially attainable efficiencies of axial flow units were higher than of centrifugal units. Even a slight differential in this component efficiency would mean an appreciable saving in fuel consumption.

The two considerations of lower frontal area and higher efficiency of an axial flow compressor were sufficient to outweigh the potentially lower manufacturing cost of a centrifugal compressor.

Figure 2 — Cutaway Sectional View of J34 Engine

With the choice of compressor made on this basis, similar emphasis was placed on the choice of the other engine components. Ideally they should have no greater frontal area than the compressor, be as light as possible, and the gas flow should be straight through to prevent the losses associated with taking high velocity gases around corners.

The choice of a combustion chamber influenced by these factors and by the need for a high energy release per unit volume centered consideration on two types. One was a "can" type in which a number of small cylindrical combustion chambers were located around the engine with the axis of the cylinders parallel to the engine axis. The other, an "annular" design, had an annulus concentric with the engine centerline into which fuel was introduced from the upstream end and air in varying amounts along the inner and outer wall of the annulus.

Earlier incorporation of a can type combustor on another engine indicated several drawbacks. One was a greater mechanical complexity and more parts since each can had to have its own combustion liner and its own outer casing. In addition, the voids between cans were wasted volume that could be used for combustion in the annular design. On the other hand, the can type could be designed so that the liners could be replaced without disassembling other major engine parts.

An annular type of combustion chamber, similar to the type used on early Westinghouse engines and shown schematically in Figure 1, had the disadvantage that considerable amount of the space available at the upstream end could not be used for actual burning. This is because of the need for a gradually widening annulus as the gases burn and progress downstream. This inability to use the available space would have resulted in a longer and hence heavier engine.

A bold but successful solution to this problem came in the choice of a double annular combustion liner, see item 7 of Figure 2. Fuel is introduced through fuel spray nozzles, 12 of Figure 2, located at the upstream end of both the inner and outer annuli. Air is introduced along both walls of both annuli. Some comments on the development of this combustion chamber to a point of unusually long life are given later in this paper.

Both a single stage and a two stage turbine were studied for this engine. The two stage was chosen because of its smaller diameter and higher component efficiency in spite of a slightly higher weight than the single stage turbine.

The choice of the three major components discussed above coupled with a simple sheet metal exhaust nozzle section resulted in the straight through unit as shown in the cut away view Figure 2.

The degree of attainment of the primary design objective, small frontal area, is indicated by the specific thrust of 570 pounds per square foot of total frontal area on the J34-WE-22, the first production model of the J34 engines. Even higher figures, up to 630 pounds per square foot, have been obtained on later models. These high specific thrust have made the engines attractive for high speed aircraft.

Location of Accessories.

An airplane power plant must supply power to drive certain airplane accessories as well as items such as fuel and oil pumps required for the engine

operation. Ideally all the accessories should be mounted on the drive pads in such a way that they are entirely within the basic engine diameter. Some turbo-jet engines have been able to do this. As the size of the power plant increases the accomplishment of this objective become less difficult. During the preliminary design stage of the J34 it was found that this objective could be achieved only at the expense of extreme complexity at the inlet end of the engine, and consequently more difficult field maintenance.

An optimum design for this size of engine was finally worked out. An auxiliary gear box capable of driving all the engine and airplane accessories was designed for mounting on the inlet bearing support as shown on Figure 2, Item 16. The inlet bearing support was then designed in such a way that it could be rotated allowing the accessory gearbox to be located at any position in increments of 10° around the engine. Actually only the five positions shown in Figure 3 were used. This design permitted the airplane designer to locate the gearbox on the engine at any angular position he chose thus allowing the attainment of maximum accessibility for all engine and airplane accessories. (The frontal area figures given earlier included the projected area of the gear box). This freedom minimized the disadvantage of having the accessories outside the basic engine diameter.

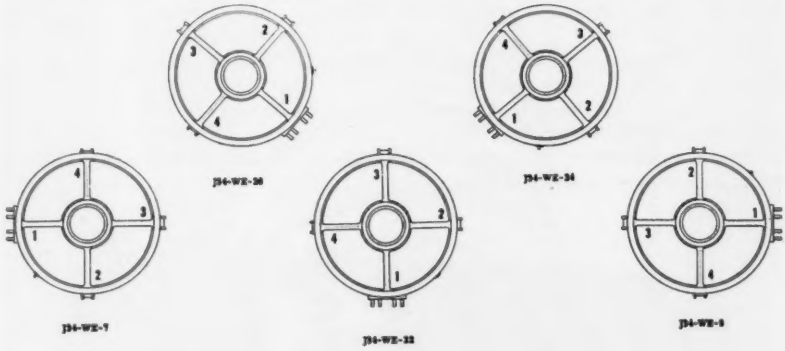


Figure 3 — Inlet Bearing Support Positions for Different Accessory Locations

J34 engines with all five of the different gear box positions have been used in the field. However, it has become more and more apparent that maintainence and supply problems are considerably simplified with only one engine configuration. As a consequence all production engines have been designed to one configuration; bottom mounted accessory gear box.

Bearings.

For airflow and stress reasons, a rotative speed of 12,500 RPM was selected for the J34 engine. Bearings had to be chosen which could operate at this speed, withstand the loads imposed by high **g** pull outs and maneuvers, and withstand angular deflections of the shaft through the bearing caused by high gyroscopic forces.

At the time the prototype of this engine was being designed there was relatively little experience available on antifriction bearings of the required sizes operating at these high rotative speeds. Marked skepticism was encountered when the possibility was first considered. From a series of tests on both sleeve and antifriction bearings it was concluded that longer life could be obtained using the antifriction type. Pitting was frequently encountered on the surfaces of the sleeve bearings. In addition, experience on an earlier engine had indicated that momentary deflections of the shaft through the bearing caused accelerated deterioration of the bearing surfaces. The need for starting the engine at low ambient temperature was another factor that contributed to choosing antifriction bearings.

The wisdom of the choice of antifriction bearings has been born out by their reliability and long life under all operating conditions. Bearing trouble has been very rare. One test engine has had over 800 hours of successful bearing operation.

To take the necessary shaft deflections at the bearing locations, antifriction bearings were developed in which the outer race was supported in a spherical seat which permitted angular motion of several degrees.

A ball bearing located at the inlet end of the compressor takes the entire thrust load as well as radial forces. The middle and rear bearings are roller bearings. The location of the thrust bearing at the front end of the engine was chosen for two reasons. First the design could be made several pounds lighter because enough structure to take the thrust loads was already located at the inlet end of the engine for other reasons. Second the ambient temperature around the bearing would be as much as 300 F cooler at the compressor inlet as compared with the compressor outlet. Because of this thrust bearing position, it is necessary to allow for differential expansion between the rotating and stationary parts in order to avoid axial rubs.

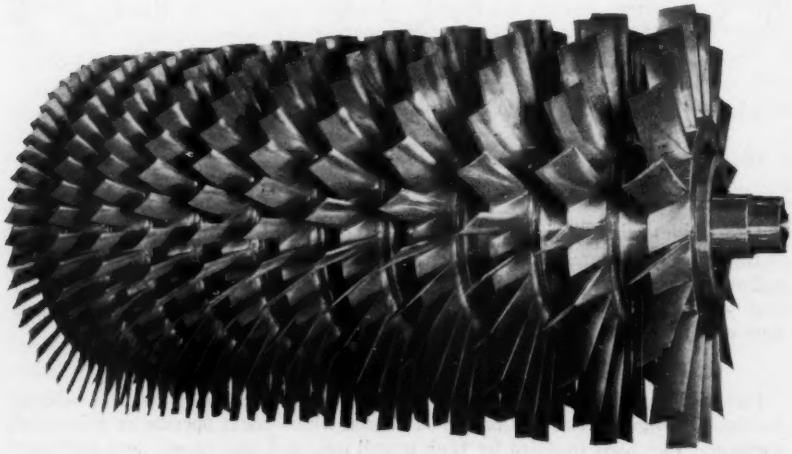


Figure 4 — Compressor Rotor Assembly

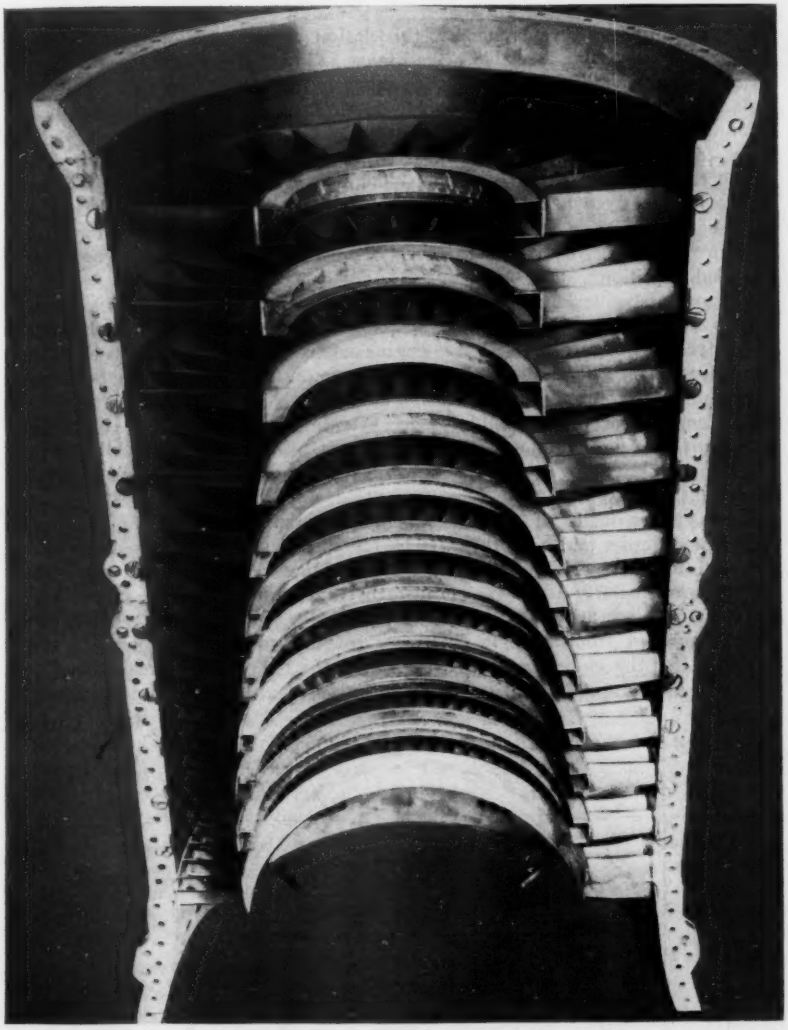


Figure 5 — Half of Compressor Housing with Vane Assemblies Installed

Mechanical Design of Compressor.

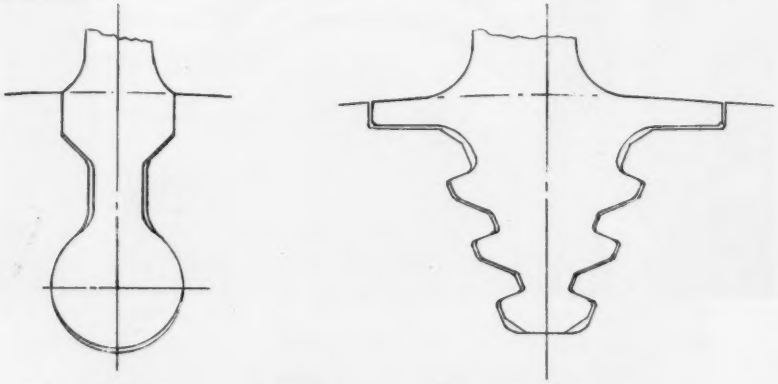
The compressor for the J34 engine consists of eleven stages including a set of stationary inlet guide vanes and two stages of straightening vanes at the outlet end. Figure 2 shows the arrangement of the compressor rotor in the housing with its stationary vane assemblies. Figures 4 and 5 show the details of the rotating and stationary assemblies more clearly.

One of the first decisions made in this design was to have an inner shroud on all the stationary vane assemblies, see Figure 5. The decision was made primarily on a basis of weight. Stationary vanes supported as cantilevers from their outer ends would have to have an appreciably larger cross section to withstand the gas bending loads and this in turn would mean greater chord length for the vane in order to maintain the same thickness over chord ratio as required by airflow considerations. This greater vanechord length would necessitate a longer engine and consequently a heavier engine. The second reason for choosing to put a shroud at the inner end of the vanes was to better withstand the vibratory forces at many different frequencies that can occur under various compressor speed and load conditions.

To prevent gas leakage around these vane assemblies from the high pressure side to the low pressure side, seal strips were welded to the inner shrouds as can be seen in Figure 5. With the engine assembled these seals fit with close clearances on seal lands of the compressor rotor. These lands can be seen on the compressor rotor, Figure 4.

The compressor vane assemblies are held in machined grooves in the cast aluminum housings. Circumferential movement of the vane assemblies is prevented by the large headed screws visible along the joint of the housing assembly, Figure 5.

Studies were made of two basic compressor spindle designs, one a single piece construction and the other a separate disc design. Analysis showed that the total weight would be about the same. However, the single piece rotor appeared particularly attractive because there was no problem of proper alignment of the discs at assembly. The design finally evolved includes a ten stage rotor, machined from a single aluminum forging, to which is bolted a single steel disc for the eleventh stage. Because of the temperature encountered, the steel eleventh stage disc turns out to be lighter than had it been designed of aluminum.



Ball Type Blade Root — Serrated Type Blade Root

Figure 6

DESIGN OF BLADE ROOTS.

Different blade root designs are used on the rotating compressor and turbine blades. Figure 6 shows the simple and less expensive ball root used on the compressor blades and the more complex but more efficient serrated root used on

the turbine blades. The serrated type of blade root is used when the radial load per square inch of circumferential disc surface is high. When heavy blades or a very large number of blades must be attached to the disc periphery the serrated root is used. No weight reduction could be achieved in the compressor rotor by using serrated roots because the axial length of these discs is dictated by the chord length of the blades. Also this axial length is great enough that the bearing area between a ball root blade and grooved slot is sufficient to carry the load.

Design of Combustion Chamber.

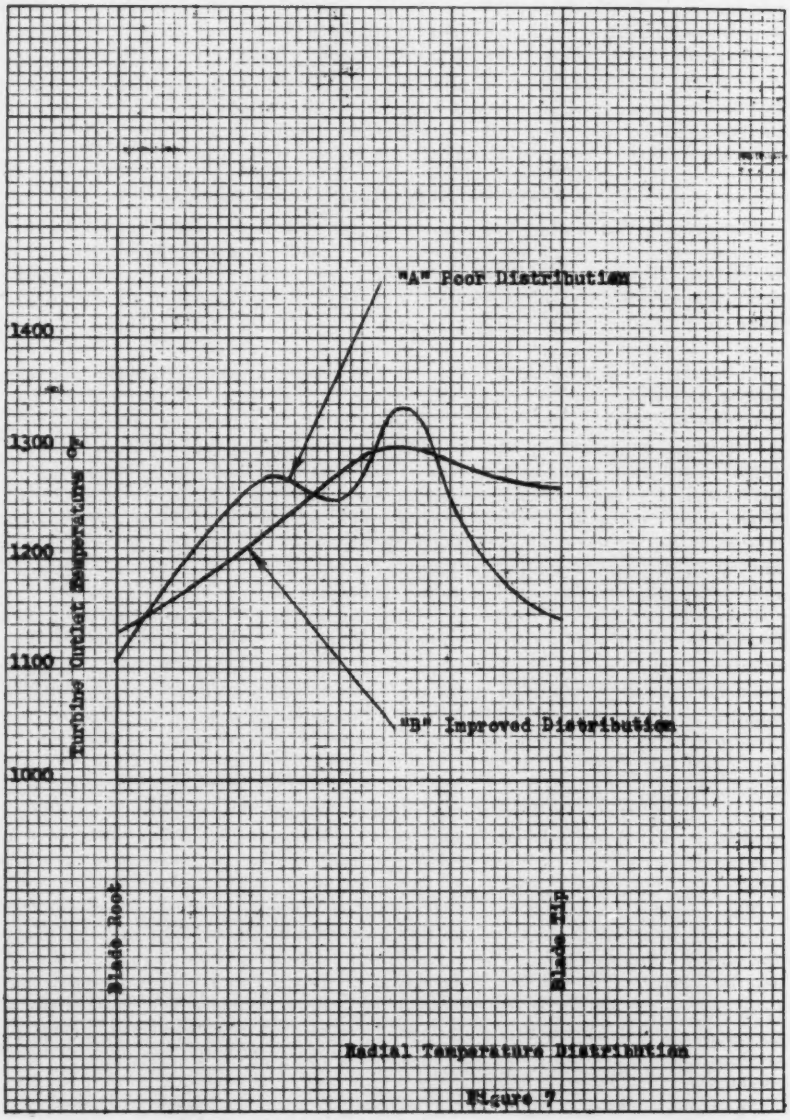
The primary function of the combustion chamber is the rapid burning of the fuel injected at the upstream end. After the combustion development program 17,000,000 BTU/hour/ft^3 were possible with an annular type of burner. However, two serious mechanical problems appeared simultaneously with the attainment of the high energy release rates. One was rotating turbine blade life: the other was combustion liner life.

The combustion products leaving the combustion chamber pass through the first stage turbine nozzle and then through the first stage rotating blades. The variation in temperature of these gases along the length of the rotating blades is important in determining how rapidly they will creep under the high centrifugal forces. If the gas temperature is high near the root of the blades where the centrifugal forces in the blades are greatest, the blade life will be short. If the base can be kept relatively cool and the tip hot, the blade life will be longer. It was found that by varying the amount of air introduced through the inner and outer walls of the two combustion chamber annuli, large variations in the radial temperature profile could be obtained.

Curve A in Figure 7 shows the radial temperature variation of the gases leaving the turbine of an early combustion liner. This temperature profile was unsatisfactory because blades occasionally burned off in line with the inner peak. Efforts were made to vary this profile by changing hole sizes to let different quantities of air through the liner walls. The problem was difficult because the changes had to be made empirically. No theory was available for accurately predicting the effect of a change in the hole sizes of the liner wall. Sometimes a hole change would give an improved radial temperature distribution but a poorer burner efficiency or a lower altitude ceiling. After many experimental models were tested a design was evolved which gives a temperature profile similar to curve B of Figure 7 and which results in long rotating turbine blade life.

The problem of combustion liner life also received vigorous development effort. Burnouts of sections of the liner were commonplace until the technique for putting a blanket of cooling air on both sides of the entire liner wall area was developed. The design feature which permitted this blanketing was a step type wall construction in which successive basket sections were separated by corrugations. The corrugations acted as a mechanical attachment for successive sections but also permitted the air to pass through and cool the wall inside the combustion area.

The three views of a liner shown in Figure 8 show the details of basket construction as well as the configuration of holes through which the air passed into the combustion area. Liners of this design have run several hundred hours without any failures or burnouts.



Radial Temperature Distribution

Figure 7

Figure 8 — Three Views of Double Annular Combustion Liner

Conclusions.

The design principles discussed in this paper have been applied to the J34 engine and have resulted in an engine with optimum installation and performance characteristics. Field operation of the engine during the past three years has shown it to have a high degree of reliability.

Recently a single J34 engine of the design currently in production successfully completed three successive 150 hour qualification tests. The qualification test schedule, drawn up by the Navy and Air Force, is intended to simulate severe field operation. Passing this test qualifies an engine for use on production aircraft. The feat of completing three successive tests is clear evidence that the new type of power plant developed during the past decade has passed through the experimental phase and has reached a status of maturity.

Official Photograph. National Military Estblishment (N.M.E.)

Skyrocket (D-558-2) IN FLIGHT—One of the first flights in which it combined rocket and jet power was made recently in the Navy's *Skyrocket.* The Douglas-built research craft took off from the desert runways at the Muroc, California test base. Developed for the Navy by Douglas Aircraft Company in cooperation with the National Advisory Committee for Aeronautics, the needle-nosed *Skyrocket* is aiding in obtaining valuable information about new power plants and speeds near the sonic range of flight. The swept-wing D-558-2 *Skyrocket* is the advanced version of the Navy's D-558-1 *Skystreak,* straight-wing red-painted jet which twice in August 1947 shattered the world speed record.

NAVAL PROCUREMENT

A Thorough Discourse on a Subject With Which All Naval Engineers who Practice the Profession Should be Familiar

CAPTAIN JOHN H. KEATLEY, U. S. N.

THE AUTHOR

After graduation from the Naval Academy in 1929, Captain Keatley served aboard the U.S.S. *Tennessee* from 1929 until 1931. He was assigned under instruction in Naval Construction at the Naval Academy Post-Graduate School for one year and for two years at Massachusetts Institute of Technology. Upon completion of this course and ancillary short courses during the summer he was assigned duty at the Naval Shipyard Mare Island serving during a three year tour as Assistant Planning Superintendent, Assistant Shop Superintendent, and Drydocking Officer. From 1937 to 1939 he served as Hull Superintendent and Assistant Planning Officer at the Naval Shipyard Cavite, P.I. In October 1939 he reported for duty to the Superintending Constructor, New York, and remained in that office when the Bureau of Engineering and Construction and Repair combined into the Bureau of Ships and the Superintending Constructor's Office merged with the Office of Supervisor of Shipbuilding. During this period his duty included inspection of construction of destroyers, small craft and design supervision of a variety of vessels including cruisers and jeep-carriers, amphibious types and small craft. In 1944 he was ordered to the Staff of the Commander, Service Force Seventh Fleet and acted as Chief Staff Officer for the Service Force Representative at Lingayen. After serving as Ship Maintenance Officer, Logistics Officer and Officer-in-Charge of the Philippine Army Off-Shore Patrol (Filipino Navy) on the Staff of Commander, Philippine Sea Frontier and Commander, Naval Forces Philippines, he was assigned duty as Deputy Director of Contracts, Bureau of Ships, in April 1947 succeeding to the Directorship in June 1948, his current assignment.

Procurement is the keystone in the arch of Military Logistics, wedged between and securely locking the *voussoirs* of Determination of Military Requirements and Distribution of Requirements.

...losed *Skyrocket* is aiding in obtaining valuable information about new power plants and specs near the sonic range of flight. The swept-wing D-558-2 *Skyrocket* is the advanced version of the Navy's D-558-1 *Skystreak*, straight-wing red-painted jet which twice in August 1947 shattered the world speed record.

The problems of determining immediate requirements and distributing them are only too familiar to the average line officer, particularly to those who served in forward areas during the war. Understanding of procurement, however, is far less general as it nearly always relates to obtaining materials from civilian industrial or commercial sources. Even the number of experienced Supply Officers well versed in the technique of present-day military procurement is surprisingly small.

My introduction to Navy procurement began with my participation in the Far Eastern Rehabilitation program in the Philippines in 1946. It serves to illustrate the diversity of situations which must be dealt with through the medium of a contract and further emphasizes the need for wider Naval knowledge of procurement.

With ships to repair and physical facilities in abundance but without the motivating power of the men who had departed in the happily conceived but locally devastating process of demobilization, the fortunate coincidence of agressive Industry in search of postwar work gave the initial clew to the solution of the problem. Recognition by Naval authority in Pearl and Washington of the need to apply wartime use of civilian contractors to immediate postwar problems furnished the inspiration; understanding and cooperation on the part of the local command furnished the confidence; and the gleeful eagerness of a group of wartime shipbuilders with no more ships to build provided the nerves and sinews of the undertaking.

As part of the gigantic mass of surplus war materials to be disposed of were hundreds of ships and craft—Army, Navy and War Shipping Administration—to be sold primarily to facilitate Far Eastern economic recovery by providing "operable" water transportation. The stipulation, "operable", was the heart of the problem because, even during the war, many ships, later surplus, had been kept "operable" only by the grace of God, chance windfalls of spare parts, the heaven-guided presence of civilian technicians, and the superhuman efforts of Navy engineers. After demobilization, the local Navy alone could not keep unmanned ships operable while awaiting sale, nor get them operable again when lay-up under conditions of tropical deterioration, cannibalizing and occasional pilferage had reduced some to derelicts.

On a May morning in 1946, the Seabee Commodore on the staff of Commander, Philippine Sea Frontier, Manila, phoned the Ship Maintenance Office, "The Admiral sent a Mr. H--- and a Mr. L--- of the ------ Corporation to see me. They are out here looking over the general situation; apparently they are interested in ships so I'll send them to see you."

The gentlemen arrived escorted by a Filipino messenger. "Captain, Commodore H--- sent these gentlemen, sor."

Introductions were made and the inevitable coffee was offered and accepted.

"I understand you gentlemen are interested in repairing ships."

"We could be; we have a letter of introduction to the Admiral from Admiral ----. We're out here trying to see what sort of prospects there are. We still have a nucleus of supervisors left at our West Coast Yard and want to use all of them, if possible, before the team gets broken up."

"Have you seen Samar yet?"

"No."

"Would you care to go down there?"

"We'd be very much interested."

"Well, this is Friday. I think I can get you on a plane down there tomorrow—that should get you back on Sunday. Will that be convenient?"

"Certainly."

And so it started. Sunday Messrs. H--- and L--- returned elated about the repair layout at the ship repair base at Samar with plans already framed as to how their people would fit in. We made a rough outline of the project.

The conference dissolved on this note: "We'll call Los Angeles tonight and I think we can go to work for you."

The company's Los Angeles office approved and the Navy authorized the local command to extend a "Letter of Intent". Action began at once with the arrival of three chartered plane loads of American civilians and the dispatch of Filipino labor recruiters to Cebu, southern Luzon, Leyte and Samar. I was to discover later that I had blithely stepped in where lawyers, if not angels, usually fear to tread and that through the medium of the Letter of Intent unwittingly had opened Pandora's sea chest and misplaced the key. But work was starting and we were actually beseeching the State Department's surplus disposal agency to sell some ships so the Navy could repair them.

September 10—dispatch from BuShips to ComNavPhil—(Phillippine independence of July 4, 1946 caused among other changes the change of name of the Naval Command from ComPhilSeaFron to Commander Naval Forces Philippines.) "Request your representative and Mr. H---, of ------ Corporation Washington earliest to negotiate contract NObs---- for which you issued Letter of Intent."

September 11—dispatch from ComNavPhil to BuShips—"UR ------ X Both Mr. H--- and Ship Maintenance Officer urgently required Philippines to organize surplus ship repair program X Request you send representatives Manila to negotiate."

September 13—dispatch from BuShips to ComNavPhil—"UR ----- X My ----- X Impractical send representatives Manila X Request Mr. H--- X Ship Maintenance Officer arrive Washington prior 30 September."

And so Mr. H--- and I arrived in Washington in late September. Then began my procurement education; in turn, I think there began an education concerning the Philippines to those involved in the contract who had never been there. There certainly started to develop a

mutually deep appreciation of the power and danger of a "Letter of Intent", a piece of Contracting Officer jargon as familiar in procurement as "topside" is to those whose Naval existence has not yet been complicated by procurement.

Immediately upon arrival in Washington, I reported to the BuShips Contract Division, still resentful that two key people—one Navy and one contractor—had to be pulled off a new job at its start to discuss details of a contract. Very quickly the reasons behind the contemptuously received words, "Impractical send representatives to Manila" became apparent—the reasons now, 24 months later are even more clear. I learned to appreciate the rules and procedure involved in negotiating a contract, particularly a large one, complicated by all the special features involved in a new project and compounding usual complexities of labor, transportation, etc. by a foreign locale. I discovered that "representatives" involved the Bureau of Ships for only one; the Secretary's Office was interested for reasons of business approval and along with the Bureau of Yards and Docks because of the labor relations and labor rate effect of the ship repair contract on Y&D dry dock preservation work already underway in the area; Naval Operations, the Judge Advocate General's office and the office of Naval Intelligence were interested for reasons of transfer of ships and the legal aspects thereof, and because of relations with the State Department which involved passport clearance for American civilians into the new Philippine Republic; Bureau of Supplies and Accounts was interested because its Cost Inspection personnel had to be on the job; and finally the Office of General Counsel was deeply involved because it had to write the contract. Further, it was obvious that successful negotiation could be accomplished in Washington only in the presence of area service and contractor personnel intimately familiar with and partisan to Philippine conditions, requirements, and purposes.

It was obvious also that there was much more to be said by a lawyer's standards, than was speedily and briefly included in the two page telegram by which a large operation involving the employment, transportation, feeding, housing, hospitalizing and insuring several thousand Filipinos and Americans had been set in motion.

In the eyes of those experienced in such transactions, who lived comfortably amidst the confusing routine surrounding large contracts, the telegram left much to be desired as far as adequately protecting the Government's interests. It seemed to me after a private session with the initiate, that there was little doubt but that the contractor seemed more able to protect his interests in such a negotiation than was the staff of a Pacific area Commander. I should have felt ashamed that we had so deeply offended against the canons of experienced contracting but the memory of the incomparable satisfaction of seeing within three weeks 140 American civilians and several hundred Filipinos revivifying a base left desolate in spite of its material excellence was

still too fresh and strong to permit it. Instead of shame there began to sprout the seed of respect and admiration for the speed and competence with which the Navy's officer and civilian contracting personnel swallowed their chagrin at the naivete of the "Letter of Intent" and began to frame a complete and equitable contract around the sketchy initial statement of the idea. I say, "Seed began to sprout" rather than "Flower began to bloom" because after an absence of two years, I found postwar Washington hard to comprehend. It was difficult to realize that in true perspective the Philippine problems which to us there loomed clear, if colossal, were simply another dot on a world plot of headaches.

The contract was negotiated and signed; the forward area promoters departed within the space of 10 days after their arrival in Washington —a BuShips record for such a transaction. I left with the sense of relief which comes after brief exposure to new and confusing things. I left also with the promise or threat of orders to BuShips as a contracting officer upon being relieved in Manila; a copy of a large pamphlet entitled, "Buying A Navy"; and a feeling of puzzlement as to just how I had become involved in this thing anyhow—how I had signed up for a thing which maybe Supply Officers were supposed to know about but a subject that to me in common with other line officers or engineers seemed to be an evil to be avoided like a midwatch.

I returned to the Philippines and in the five months which elapsed before taking up my duties in Washington continued to be engrossed in the details of "Operable" ship disposal, with only quarterly reminders of procurement when the contract estimates for the next period were submitted. However, I was provident enough not to misplace the pamphlet "Buying A Navy", and during my leave obtained a sketchy background on what this entailed.

Pre-War Purchasing Procedures.

According to this pamphlet, prior to the war and in common with most all Government purchases, Navy buying was done on the basis of formal advertisement and competitive bidding, with the award to the lowest qualified bidder. This procedure was the rule from the largest vessel down to the smallest undershirt. As a corollary, even though the technical bureaus developed requirements and prepared specifications, the purchasing functions were carried out by the Bureau of Supplies and Accounts, with the exception of vessels, where bids were opened in the Secretary's office. Some purchases were exempt from competition; (1) those obtainable from the Procurement Division of the Treasury, Federal Prison Industries, Institute of the Blind and Indians; (2) those for which competition was impracticable (proprietary items); (3) military articles bearing a security classification; (4) those where immediate delivery was required for emergency reasons; and (5) those costing less than $500. Policies were set forth in U. S. Navy Regulations and Bureau manuals.

Restlessness caused by chafing under the yoke of enforced competition first appeared as early as 1919, when it was recognized that it was not to the best interests of the Government so to purchase aircraft. The problem was studied by executive boards and Congressional committees, and the end result was the Air Corps Act of 1926. This method provided for the submittal of new designs in competition solicited by advertising; the winner, if capable of reducing his design to practice and at a suitable price, was awarded a contract for production. If the design winner could not produce or could do so only at an unsuitable price, the design, only, could be purchased at a price not higher than that quoted in the original submittal. Only nine paper plane competitions were held between 1926-1938 and only one between 1927-1935.

Acknowledging that this method was unworkable, the Army resorted to use of the authority (Act of 2 March 1901) under which proprietary articles could be purchased without competition. This practice led to the Foulois Investigation of 1934 which censured the practice.

Further search for relief led to the adoption of sample aircraft competitions. Here sample aircraft were submitted for inspection; test performance and engineering characteristics were evaluated by a committee of technical officers and utility characteristics by a second board. Upon advise of these committees, the Secretary of War determined the winner and announced the results publicly. Awards could be made to three winners at negotiated prices not exceeding figures in the bids. Also, under authority of the Act of 5 April 1939, awards of sample airplanes could be made to not more than five competitors at reduced prices as determined by the Secretary. Fifty such competitions were held from 1934 to the war.

Two additional pieces of legislation permitted exemption from competition: (1) Public Law 639, 16 June 1938, permitting the placing of educational orders by the Army to familiarize industry with production of military articles of special or technical design; and (2) Public Law 168, 13 July 1939, provided that aircraft parts, instruments, aeronautical accessories requiring security classification could be purchased by the Chief of Air Corps as he deemed most economical or efficient. Limited appropriations precluded extensive use of (1) and use of (2) was hampered by the restriction that no purchase could be made until the Secretary of War certified the need for secrecy and then only after submitting proposals to three reputable concerns.

During this period exceptions to the general rule of advertising in shipbuilding were the carriers *Saratoga* and *Lexington*, the hulls of which had been originally laid down as battle cruisers but which having been cancelled as such under provision of the Treaty Limiting Naval Armaments of 1922 were completed as carriers on cost-plus-a-fixed-fee negotiated contracts by New York Shipbuilding Corporation and Bethlehem, Fore River. However, *Pensacola* and later cruisers and

Farragut and later destroyers were contracted for as a result of competition.

Defense Period.

It is seen from the foregoing that until the defense period, beginning 1939, little real deviation from the fixed rule of formal advertising and competition occurred. The early anticipated requirements for the war which it was apparent was soon to follow, indicated at once that further liberalization of peacetime methods of contracting would be required in order to deal expeditiously with larger and more complex purchases.

In constructing outlying and foreign bases and aircraft facilities, there was no background for determining costs and the scope of such undertakings limited the field to a very few so that competition was in fact impracticable. These conditions were appreciated by Congress which in April 1939 passed Public Law 43, 76th Congress, appropriating funds and authorizing the use of cost-plus-a-fixed-fee instead of the usual fixed-price contract which was the rule under formal advertising. At this time also, statutory limitations of profit were imposed which were related to the amount of risk in the undertaking (much of which was underwritten by the Government).

To limit excessive profits, procurement of ships and both Army and Naval aircraft was accomplished under the Vinson-Trammell Act, which provided profit limits of 10% of allowable costs. Profit limitation was reduced to 8% in 1936 and raised to 12% for aircraft in 1939. However, the second Revenue Act of 1940 rescinded, on 31 December 1939, the Profit Limitations Statutes as applying to military and Navy contracts and subcontracts where the prime and subcontractors were subject to excess profits tax.

On 28 June 1940, Public Law 671 eliminated the requirement for advertising and competitive bidding for Naval vessels and aircraft and permitted also the use of cost-plus-a-fixed-fee contracts (earlier authority permitted this on construction contracts only); advance payments acquiring and furnishing of facilities to contractors; and other liberalizations. Profit on fixed price negotiated contracts was limited to 8% of estimated contract price; at the same time a profit limitation of 7% was placed on cost-plus-a-fixed-fee contracts.

Whenever practicable, the last prices for similar items bought under competitive contracts were used as a guide for reasonableness of current negotiated prices but where no previous price history existed the contracting officer, whose sole responsibility it was to make this determination, had to do so aided only by his best judgment and by estimates prepared by engineering personnel in the activity doing the buying. Particularly in contracting for Naval vessels and aircraft, the lack of any previous experience in this new technique of negotiating required that existing procurement personnel, usually commissioned officers in

the regular service, be utilized. Generally, early contracts for aircraft were of a cost-plus-a-fixed-fee type and contracts for vessels were of a fixed-price adjusted type.

The first two large Naval expansion programs called for first 11% and then 70% increase in existing displacement tonnage. With such huge orders in an industry which theretofore had only comparatively small amounts of work, the large number of ships included in these programs had to be allocated in such a way as to make best use of existing shipyard facilities and as a result prices were negotiated in advance between the top company officials and the senior technical officers of the Navy. By this procedure it was possible to issue Letters of Intent to all contractors on the very day when the authorizations for these vessels were signed by the President. Since it was mutually understood by the Navy and Industry that many factors materially affecting costs during the long periods of performance could not be anticipated, prices were agreed upon which were admitted to be high. Gentlemen's agreements, however, were made that if savings in actual cost as compared to the estimates were realized the shipbuilders would voluntarily reduce contract prices in order to avoid excessive profits. As a commentary on the justification of this mutual trust between the Government and Industry, there is no record of any failure to honor these agreements; however, had there been a failure to do so, the Renegotiation Act was already law and the same effect would have been accomplished by renegotiation.

This practical approach to the problem of pricing permitted expeditious prosecution of ship construction so vital to National Defense. The same procedures extended to the later programs of 1941 but thereafter a gradual tightening of pricing procedure began to develop.

Since Public Law 671 mentioned above, as far as the Navy was concerned did not not permit negotiating rather than advertising in the case of general supplies, these still had to be purchased by competition; for this reason Navy purchasing agencies procuring supplies did not feel the impact of the change in purchasing methods until after the passage of the First War Powers Act in 1941.

In dealing with this new problem of negotiating, the first technique was to use group rather than individual participation on the Navy's side with a later review and ratification of proposed agreements by formal or informal groups of officers. Such a procedure safeguarded the Government's interests, eliminated favoritism and to some extent offset the lack of trained negotiators. Contracts made under this system accordingly represented the best collective judgement rather than an individual opinion, and spread the large responsibility among a group rather than centering it on a single officer. This procedure inspired by expedience later formalized itself into the team system of negotiating where teams consisting of a contracting officer, technical, legal, and

business specialists took the field for the Navy against the best negotiating talent the contractor could put forward.

The inadequacy of the peacetime competitive bid system gradually manifested itself as the huge increase in Government purchases resulted in the creation of monopolistic markets and disturbance of normal market relationships which automatically operated to control peacetime prices. Specific defects of the system were: bidders lists assumed an enormous size; delays in advertising and bidding could not be countenanced; business could not be so distributed as best to utilize existing facilities; consecutively increasing prices for the same articles were received because of lack of competition; and small industry was unable to obtain primary contracts.

Even after authority was granted to renounce formal advertising, history indicates that informal competitive bidding continued and even increased. This was the natural effect of the volume increase of purchases and the early lack of proper organization and trained personnel for implementing negotiating authorizations. It was noted, however, that where bona fide competition could be obtained in certain classes of commodities from selected sources, work was greatly reduced by this method and suitable prices were obtained.

With the removal of performance bond requirements and with advance payments to finance contractors, purchasing personnel had the great responsibility of investigating competency of suppliers to insure satisfactory performance, particularly as to meeting promised dates of delivery and exacting specifications.

Wartime Purchasing Procedures.

Eleven days after Pearl Harbor the First War Powers Act was passed. This statute granted general authority for the use of negotiation rather than advertising; the right to waive payment and performance bonds; and the right to amend, modify or change contracts whenever it would facilitate prosecution of the war. Some purchasing agencies did not immediately take advantage of the freedom granted by this authority to negotiate for supplies whereas the new procedures had already been started in the case of aircraft and ships.

War Production Board Directive No. 2 issued in March 1942 generally prohibited purchase by bidding methods and required that the prices be negotiated except in limited cases. This directive implied lack of prompt initiative on the part of some activities to avail themselves of the new authority to negotiate and the record indicates that there was resistance by some of these agencies to change from old familiar methods. This was undoubtedly the result of inertia, the lack of proper organization and personnel to deal with negotiating techniques. The same directive required contractors to furnish a good deal more information about their businesses than had previously been required; balance sheets, profit and loss statements, estimates of projected costs,

machinery and tooling and other related information now had to be submitted.

The more detailed requirements of this directive pointed out more greatly than before the crying need for procurement officers of ability and experience not normally found among regular officers, even among those accustomed to purchasing for the Navy under the old system. Negotiators of the new type contracts had to understand private business psychology, organization and management; to be familiar with fiscal, production, and legal problems; to be able to evaluate managerial and financial capacity.

The Under Secretary of the Navy decided that the solution to the problem required recruiting specialists to act in an advisory capacity to contracting officers in fields of law, finance, insurance, industry cooperation, price analysis and negotiation. It was not immediately clear exactly how these specialists would operate but it was recognized that they should participate in negotiations from their inception until a complete agreement had been reached.

In order to clarify the problem, it is necessary to furnish additional information here as to some of the details involved. Procurement requests for purchases usually originated with technical personnel who have been allocated funds to purchase equipment or supplies in authorized programs or projects. Under the advertising system, requests were channeled through technical hands to the Purchasing Activity (Bureau of Supplies and Accounts) where schedules were prepared, bids invited, bids publicly opened, bids evaluated, notices of award forwarded, and contracts prepared and executed. When the procurement system changed to negotiation, procurement requests in essentially the same form followed the same channels. Instead of being advertised, procurements for technical material stopped in the hands of the negotiating personnel in the technical bureaus rather than continuing to the Bureau of Supplies and Accounts. Initially, negotiation was considered merely a formality, an automatic procedure, or even an onerous delaying step in the execution of the contract. One result of this attitude was that engineering personnel discussed prospective contracts with the contractor in considerable detail in terms of production, manufacturing techniques, schedules and other factors unrelated to the fiscal aspects of the contract. These discussions resulted in embarrassment to contracting officers because tentative agreements reached thereby were sometimes considered binding commitments and since they usually did not incorporate contractual considerations, a few contracts may have been unwisely issued because of the contracting officer's desire to make good the commitment of a technical officer. In such cases, the negotiating function became merely a rubber stamp and resulted in contracts which were not advantageous to the Government.

Negotiators attempted to price contracts so as to produce low cost

operations by the contractor; cost control, not profit, was and remains the basic objective. To accomplish this, negotiators sought all possible sources of information about the contractors' operations. In general, such investigations examined price comparison, price indices, operating data, renegotiation data, engineering estimates and information supplied directly by the contractor. Price analysis groups were established for the purpose of furnishing recommendations to the negotiator. In addition to price, other factors were involved such as delivery, ability to manufacture to the required degree of quality or excellence, volume and many others.

Public Law 413.

The foregoing outlines briefly the history of the pre-war procurement and the procedures used during the wartime period. I acquired a portion of this brief background in my perusal of the pamphlet "Buying A Navy" and arrived on the scene of my new operations as a Bureau of Ships Contracting Officer with no little trepidation. The topic of greatest moment was the predicted legislation which would replace the War Powers Act under which the Navy was then operating and would, it was believed and hoped, return to the pre-war basic concept of competition, still retaining the use of negotiating procedures the necessity for which was so clearly demonstrated during the war. The bill was the result of untiring efforts on the part of top service procurement personnel to preserve for peacetime the benefits of wartime experience and thereby to simplify a future mobilization. Passage of the law was predicted for the early fall of 1947; however, the legislative schedules precluded its passage until 19 February 1948 with its date of effectiveness three months later, 19 May. Meanwhile, through Congressional hearings, it was felt that the provisions of the new statute could be accurately enough predicted in advance so that early practice in operating under the new regulation could develop skills during a period when insurmountable difficulties could still be legally dealt with under the greater freedom permitted by the War Powers Act. As a guide in implementing this policy, Navy Procurement Regulations were issued in November 1947. By January 1948, most Bureaus were operating under the new procedure if not comfortably, still in a practical way.

The philosphy of the new law is best expressed by quoting the foreword of the Armed Services Procurement Regulation, sections of which have already been issued and the remaining sections of which are in preparation pending an early release:

> "The Armed Services Procurement Regulation, hereby issued by the Departments of the Army, Navy and Air Force, appreciably changes the procurement policies and practices of the three Departments under the First War Powers Act, and provides for new procurement policies and practices, on and after 19 May 1948, under the Armed Services Procurement Act, Public Law 413, 80th Congress.

When the President signed the Armed Services Procurement Act on 19 February 1948, he wrote to the Secretary of Defense as follows:

> "The Act states the basic policies of the Government with respect to procurement by the Armed Services. It declares that a fair proportion of all procurement shall be placed with small business concerns. It also states that all purchases and contracts for supplies and services shall be made by advertising, except under circumstances specified in the Act where exceptions to this general policy may be made.
>
> This bill grants unprecedented freedom from specific procurement restrictions during peacetime. That freedom is given to permit the flexibility and latitude needed in present day national defense activities. The basic need, however, remains to assure favorable price and adequate service to the Government. To the degree that restrictions have been diminished, therefore, responsibility upon the Defense Establishment has been increased. There is danger that the natural desire for flexibility and speed in procurement will lead to excessive placement of contracts by negotiation and undue reliance upon large concerns, and this must not occur.
>
> For these reasons, I am asking you to specify detailed standards to guide your procurement officers concerning the placing of business with small concerns and the circumstances under which they may waive the general policy of advertising for bids. It is of great importance in procurement matters to establish standards and definitions to guide all personnel who have authority to place contracts. Otherwise, differences in interpretation and policies may result in imprudent contracts and give rise to doubts about the wisdom of this new procurement system."

It is believed that the Armed Services Procuremet Regulation which is now being issued carries out on a policy level the instructions contained in the President's letter. All procurement personnel are enjoined to follow strictly the standards and requirements set forth in this Regulation as well as in such implementing procedures as will be issued under it from time to time by each respective Department.

The conditions under which exceptions from advertising are permitted are summarized below:

(1) National Emergency
(2) Public Exigency
(3) Purchases not in excess of $1000
(4) Personal or professional services
(5) Services of educational institutions.
(6) Purchases outside the United States
(7) Medicines or medical supplies

(8) Supplies purchased for authorized resale (Ship's service, or Canteen Stores)
(9) Perishable subsistence supplies
(10) Supplies or services for which it is impracticable to secure competition
(11) Experimental, developmental, or research work
(12) Classified (Secret and Confidential) purchases
(13) Technical equipment for the purpose of assuring standardization and interchangeability of parts
(14) Technical or specialized supplies requiring substantial initial investment or extended period of preparation
(15) Negotiation after advertising required by unreasonable bids
(16) Purchases in the interest of National Defense or Industrial Mobilization
(17) Otherwise authorized by law

Operations Under Public Law 413.

The primary effect of the new procedure was twofold: (1) It required familiarization with the procedure of advertising after a long holiday from this method; and (2) it established the necessity of obtaining authority from the Secretary in order to negotiate a contract rather than to advertise.

To accomplish the first effect, the services of the Bureau of Supplies and Accounts were utilized for mailing, opening, and tabulating bids; technical Bureaus determined that advertising was to be used, and unlike pre-war procedure, evaluated bids and made the actual award. The second effect required an additional step in the established procedure for review and ratification of negotiations in obtaining formal approval to negotiate from the Secretary or other delegated authority before business negotiations could proceed.

Inasmuch as the General Accounting Office reviews contracts made by other Governmental agencies, great care was required to insure by the most rigid interpretation that an exception applied in each specific case where negotiation was desired; a phase was experienced wherein contracting officers had to resist the temptation to use the exception which seemed simplest to apply.

Oddly, or perhaps naturally, after the initial indoctrination into the new procedure for obtaining authority to negotiate, more difficulties were experienced in the originally simpler procedure of advertising than in negotiation.

The latter difficulties resulted from a genuine desire to comply with the spirit of the legislation and to advertise even when the peculiar requirements of a procurement did not adapt it to a process where competition is not limited and where, to award to other than the low bidder requires a factual determination that his bid is not otherwise acceptable. To advertise in connection with research, developmental,

or experimental features is well-nigh impossible because among other reasons, an unequivocal specification cannot be prepared.

An additional feature which increased the hardness of the contracting officer's lot was that the new statute increased the limits of profit from the former 7% for cost-plus-a-fixed-fee contracts to a maximum of 15% in cases of Research and Development. Present policy is to allow previous profit ratios under consistent circumstances, and to consider that profit increases alone by reason of the statutory liberalization are not warranted.

Navy Procurement Organization.

As has been stated above, pre-war contracting was done exclusively by the Bureau of Supplies and Accounts. On 13 December 1942, the Secretary authorized the material bureaus to procure those special items over which they had technical cognizance. On 30 January 1943, a General Order established the "Office of Procurement and Material" which "shall under the direction of the Secretary . . . coordinate all the material procurement activities of the Navy Department, supervise programs for the procurement of ships and material . . . and perform such other duties as the Secretary may direct." The Office of Procurement and Material included the following functions: (a) production; (b) procurement; (c) finance; (d) industry cooperation; (e) inspection administration; (f) insurance; (g) price adjustment; (h) price control; (i) price revision; (j) contract termination and property disposal; (k) coordination of procurement by the War and Navy Departments.

Early procurement and purchase policy directives were issued by the Procurement Legal Division of the Under Secretary's Office. Also, Office of Procurement and Material negotiators were assigned to all purchasing Bureaus except the Bureau of Supplies and Accounts and by this means close policy control was established. Specific OP&M authority was required by all Bureaus to contract for purchases amounting to over $200,000.

The Office of Procurement and Material was later named the "Material Division" of the Secretary's office, and additional functions including Renegotiation, Facilities Review, and Advance Payments were added.

Public Law 432 (80th Congress; 2nd Session) legally established the Material Division as the "Office of Naval Material"—"under the Secretary . . . to . . . effectuate policies of procurement, contracting, and production of material throughout the Naval Establishment."

The purchase function and other duties of each Bureau are clearly delineated in the revised Navy Regulations. Each of the following Bureaus and activities is charged with design, development, production, testing, fitting out, maintenance, alteration, repair, material effectiveness, and related functions, as applicable, to the types of equipment and material assigned for material cognizance: Bureau of Aeronautics;

Bureau of Ordnance; Bureau of Ships, Bureau of Supplies and Accounts; Bureau of Yards and Docks; Office of Naval Research; Headquarters Marine Corps; Bureau of Medicine and Surgery; and the Bureau of Naval Personnel.

Types of Contracts.

In order to give a clearer general understanding of procurement, it is felt that there should be at least a brief mention of types of contracts.

During the World War I, inability accurately to estimate costs led to the use of cost-plus-a-percentage-of-cost contracts under which the contractor was paid his costs and profit as a percentage of such costs regardless of how large the costs might become. This practice gave rise to such scandalous abuses that use of the contract was prohibited and the new procurement law makes it illegal for service contracting.

During the period between World Wars I and II, when purchasing was done exclusively by advertising, fixed-price contracts which contained labor, material, and overhead costs, profit and contingencies all within a lump sum, were the rule. Fair and reasonable prices were theoretically insured by the award to the lowest satisfactory bidder.

During World War II and during the defense period immediately preceding, cost-plus-a-fixed-fee contracts were used in place of the banished cost-plus-a-percentage-of-cost contract. This type established a profit fixed at the outset as a percentage of the initial estimated cost and reimbursed the contractor for all items of allowable costs even though they exceeded the original estimate. This contract recognized that in many cases it was impossible to provide exact specifications or to determine in advance many factors which would affect costs, but it did not provide an automatic reward in more dollars profit for exceeding estimated costs. Also, in exchange for a lower rate of profit, the contractor was protected against the dangerous risks he assumed for a higher fee under the fixed-price contract. This contract, improved though it was over its predecessor suffered the same major defect: it offered no incentive to the contractor to hold costs down.

For ship repair work where the extent could not be estimated immediately upon the ships' arrival at a yard, the "Time and Material" contract was used. Under this arrangement recorded material costs were directly allowed; other costs were billed on the basis of the hours of labor used. The hourly billing rate for labor included all other charges: overhead, profit, etc.; such rates were usually established by negotiation.

Since the war, fixed-price contracts are used in formal advertising. In negotiation: fixed-price contracts; variations of this type which provide for price redetermination; and cost-plus-a-fixed-fee contracts all are used. In procurements for research and development, where exact specifications cannot be drawn, and particularly in the "blue sky"

variety where the ultimate aim of the contract may be doubtful of achievement, cost-plus-a-fixed-fee contracts are almost invariably used. Occasionally, as an encouragement to the contractor to hold costs to a minimum, the so-called incentive type of contract is used. In this type, the contractor is permitted to increase his profit by sharing in cost savings which he is able to effect in the original or target price of the contract.

For emergency repairs, and for overhauling of vessels in the reserve fleets where civilian repair facilities must be utilized, the so-called Master Ship Repair Contract is used. Strictly speaking, this is actually not a contract until work under it is assigned but it provides the general provisions and restrictions governing the work to be performed under it. These contracts are executed between the Bureau of Ships and contractors recommended by Industrial Managers. When repair work is available, bids are requested from holders of these contracts and the award of individual work on a job order basis is made to the lowest satisfactory bidder.

The contract forms discussed above are equally applicable for the purchase of supplies, for the manufacture of technical equipment, and for contracting for services.

"The Letter of Intent" referred to with apprehension in the beginning of the article is not a complete contract. It is a device which permits work to commence at an earlier date than would be possible if a complete formal contract were prepared. As the name implies, it expresses the intent to contract and establishes binding obligation to perform; its brevity and simplicity permit its immediate issue and thereby a more expeditious commencement of work while the complicated details of the eventual contract are being discussed. Since sometimes unavoidably, a considerable period may elapse prior to replacing the Letter of Intent by a formal contract, some difficulty may be experienced later in expressing the original intent. As a consequence of this feature, and for other obvious reasons use of the Letters of Intent should be confined to emergency situations.

Procurement Coordination.

Contrary to a somewhat common concept, quite extensive procurement coordination existed between the Army and Navy and between the Navy and Army Air Corps—now the Air Forces—prior to the passage of the National Security Act of 1947, which by law unified the services. This joint purchasing was principally in the field of aeronautical equipment and electronics, wherein the Signal Corps, Air Corps and Navy purchased similar equipment for each other.

Under the National Security Act coordination had been formalized and there are now three major types: (1) buying where the total procurement of an item is assigned to a joint purchasing agency staff of Army, Navy and Air Force personnel: medical supplies and petro-

leum products; (2) collaboration of buyers where contracting officers of the several services concerned are located together but contract separately: paper and textiles; (3) single service or cross procurement where one agency purchases total requirements for the National Military Establishment: Landing Craft, lumber, hand-tools and a present list of about thirty other items.

The National Security Act also established the Munitions Board which beginning in August of 1945 had been reconstituted as the Army and Navy Munitions Board. Its duties and responsibilities are summarized by the following excerpt:

"It shall be the duty of the Board under the direction of the Secretary of Defense and in support of strategic and logistic plans prepared by the Joint Chiefs of Staff—

(1) to coordinate the appropriate activities within the National Military Establishment with regard to industrial matters, including the procurement, production, and distribution plans of the departments and agencies comprising the Establishment;

(2) to plan for the military aspects of industrial mobilization;

(3) to recommend assignment of procurement responsibilities among the several military services and to plan for standardization of specifications and for the greatest practicable allocation of purchase authority of technical equipment and common use items on the basis of single procurement;

(4) to prepare estimates of potential production, procurement, and personnel for use in evaluation of the logistic feasibility of strategic operations;

(5) to determine relative priorities of the various segments of the military procurement programs."

The Armed Services Procurement Regulation is the first complete joint regulation for procurement. Necessarily, close cooperation exists and is being futher developed among the three services to achieve uniformity of policies and procurement methods. Necessarily also, the habits acquired by each service and psychology which created these habits present some difficulty in reconciling disparity of concept and practices. Such differences are believed most largely to be the result of organization differences. As a greater understanding develops, increasing benefits of inter-service uniformity and consistent style in the treatment of Industry will be achieved.

In order that this cooperation be properly developed and coordinated, many joint committees are operating and the Munitions Board Procurement Policy Council is established for digesting and finally ratifying recommendations of these joint committees.

Coordination and cooperation are being developed not alone among the services but also with Industry through the efforts of individual corporations and trade organizations. Results of these efforts are already great and the continuance of this collaboration will be invaluable.

Procurement Personnel.

As in any major readjustment, adapting purchasing habits, developed during the war to peacetime and concurrently attempting to preserve the benefits of war experience for expeditious peacetime use and for greater facility in again changing from peace to a mobilization status, present many problems. Foremost among these, perhaps, is personnel. The Navy's present purchasing establishment requires the service of approximately 2000 civilians involved directly in procurement at a total salary of in excess of $6,500,000, plus slightly less than one-tenth that number of officers. This figure includes personnel in the Bureaus of the Navy Department, the Office of Naval Research, Marine Corps and personnel located both in Washington and in field purchasing activities.

During the war as has been previously indicated, the Navy was assisted in its change-over from advertising to negotiating by the invaluable services of key personnel experienced in civilian life with the various functions of procurement. After the war, the return of experienced business executives to their previous activities left the remaining personnel in service procurement lacking by comparison the instinct, background and years of experience these men possessed.

In addition, the cancellation of renegotiation of contracts as an overall safeguard against excess profits created an additional burden on negotiating personnel in that the negotiation itself was in many cases the only insurance that profits as well as costs were not excessive. The advent of peace also appears to have developed an attitude on the part of industry of resenting restrictions imposed by the new procurement legislation; this attitude is no doubt the creature of a commercial boom era and a reluctance during it to adhere in Government business to pricing policies established during the war on Government contracts which constituted total business.

The Navy, in facing this personnel problem, suffers from the fact that Government service, even considering the compensating advantages of leave, sick leave and retirement benefits, cannot compete salary-wise with industry, particularly in a procurement field where competition is very keen. It is significant in terms of essential values that a good negotiator in a single contract may save the Government many times his annual salary. A further problem in this regard is that the field itself is highly competitive and there is a fairly large turnover; the Navy must expect that its better people as they develop will receive more attractive offers from industry and hence should be prepared to replace able negotiators lost in this way by younger men.

At the present time there is no formal recruitment pool or training program established automatically to supply such civilian talent, but studies are being conducted more exactly to classify procurement positions.

In the case of officer personnel, many of those who developed experience and talent during the war are now retired or through increased

seniority occupy billets which do not permit utilizing their services in actual negotiation. The situation as regards officers however is perhaps more fortunate in that the Armed Services Industrial College is an efficient training school in the theory of service procurement. The College is an educational institution under the Joint Chiefs of Staff, on the same level as the National War College. Its mission and scope include, among many other studies, the study of the procurement, production and distribution aspects of mobilization for war and reconversion to a peacetime basis.

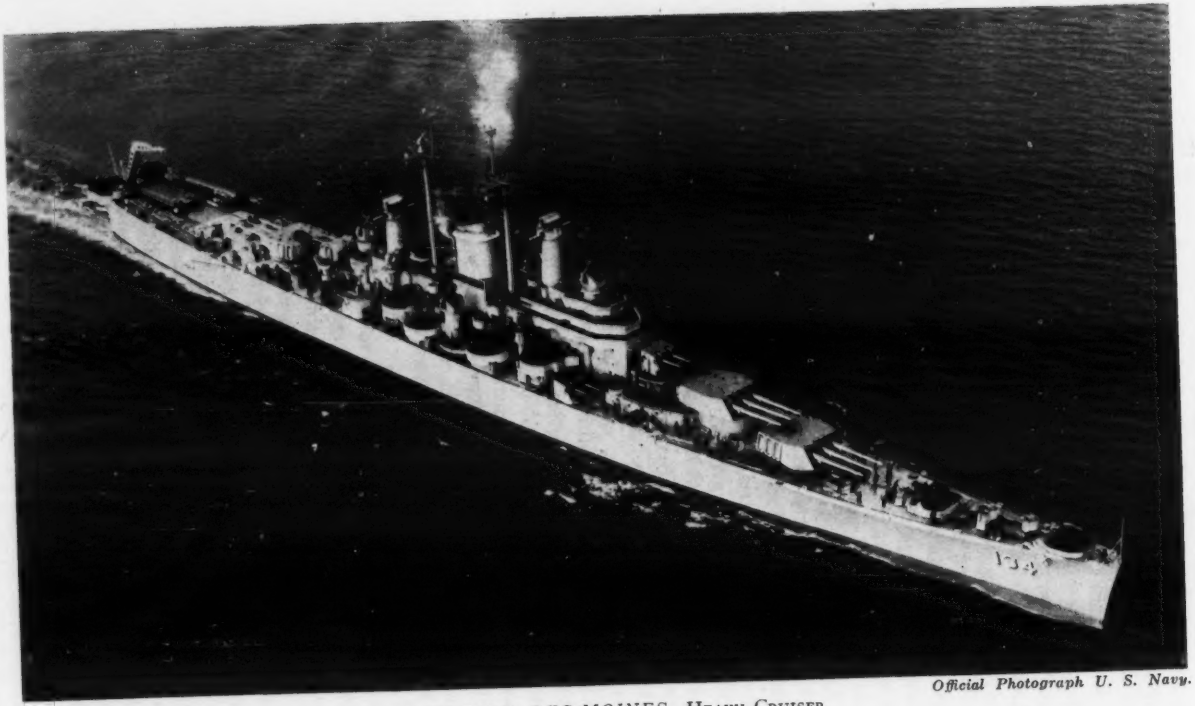
The foregoing attempts to illustrate the variety of situations within the scope of procurement by an example; briefly to outline its naval history; to discuss its legal and practical aspects; and to reveal some of its problems. Its intimate position in all naval planning, present and future operations, maintenance and expansion is at once obvious.

As Armed Service needs demand greater quantities and more complex types of services, materials, and equipment, it is becoming increasingly true that these requirements can only be filled through the use of civilian industrial and scientific facilities. This fact in itself dictates the need for greater service familiarity with Industry: its psychology, customs, and methods. For the Navy intelligently to cope with this problem requires among other things the development of understanding, experience, and skills on the part of its procurement personnel.

The bewilderment and instinctive reluctance with which I began my indoctrination into the mysteries of procurement have been replaced to a large extent by a profound interest and respect for the incidental knowledge which is a requirement for intelligent and effective contracting. I have also developed, to my own surprise but in common with more experienced negotiators, considerable zest in the competition of negotiating; the deep satisfaction which results from a contract well made.

Aside from the immediate intrinsic value to the Navy of every beneficial contract executed, there is the secondary and broader benefit in the education of officers who, through this experience can eventually talk on even terms with responsible, high-salaried business executives, thereby developing on the part of Industry a feeling of greater trust, understanding, and respect at a time when service needs and those of the country as a whole become increasingly similar.

John Paul Jones' prophetic concept as expressed in his historic letter written in 1775, of the almost impossible versatility of a Naval officer, "It is by no means enough that an officer of the Navy should be a capable mariner," recognizes the need for the development of new skills to meet new problems. It is accordingly considered the responsibility of all officers of the Navy, not only those actually engaged in procurement, to recognize procurement as a military function and to accept it as a subject to be understood along with the more classical and traditional phases of a Naval Officer's career.



Official Photograph U. S. Navy.

CA-134 U.S.S. *DES MOINES*—HEAVY CRUISER.

EXAMINATION OF SURFACES

Permanent Records by Use of Negative Reproduction of Surfaces by Plastic Castings

JOHN W. SAWYER

THE AUTHOR

JOHN W. SAWYER received his B.S. degree in E.E. from N. C. State in 1933. He served a number of years in the merchant marine. In 1942 he entered the Navy. Since release to inactive duty he has been active in the main propulsion reduction gear development program of the Bureau of Ships.

I. SUMMARY.

Permanent and accurate three dimensional records of surface finish and damage can now be made. The process is simple and can be used by inexperienced personnel without weighing or heating equipment. The record is made by casting onto the surface under study a thermosetting resin which hardens in approximately twenty minutes after the addition of a catalyst. The resin and catalyst are preweighed and packaged in small containers ready for immediate use. External heat and pressure are not required. After the resin hardens the casting is removed for study. The negative replica may be tested with a profilometer or similar surface measuring instrument without damage to the casting. Gear teeth, shafts, bearings, journals, headers, valves, cylinders, rolls, screw threads, machine ways and other parts may be inspected and facsimile records made by use of resin casting. This method of recording surface conditions is considered an invaluable tool for research, test, development, manufacturing and inspection facilities.

II. Introduction.

The problem of recording surface conditions of mechanical parts that are subject to frictional wear, chemical action or erosion, is one that has received a great amount of attention by investigators during recent years. It is, of course, readily apparent that accurate factual records of surface conditions of piston rods, cylinder liners, valve seats, tubes, turbine blades and other items are valuable and essential data for the designer, the manufacturer and the operator of equipments.

A story of surface conditions of parts may be compiled by sketches, photographs and impressions. The sketch method is one that requires experience and skill to present a record that is accurate and easily understood. Photographs are valuable and permit the recording, in a general way, of surface conditions that do not lend themselves for easy reproduction by sketches. The work necessary to make a realistic photograph of certain parts given under ideal conditions may be of such magnitude that the delay and expense involved would outweigh the advantages of a pictorial record. The negative replica method as described in the following pages, lends itself readily to recording the damage and finish on practically all types of surface.

The practice of making a negative replica of a surface is not new. Various materials including wax, sulphur-graphite, and low temperature melting alloys have been used. Investigations have been conducted by Pearson and Hopkins to obtain negative replicas of surface finishes by employing a thermosetting plastic whereby the plastic is moulded on the surface under study by the application of external heat and pressure.[1] Additional work has been done by Timms and Scoles with plastics, where the surface of the plastic is softened by action of a solvent and then pressed against the area under study and allowed to harden.[2] These methods are apparently capable of accurately recording surface conditions. However, they are not readily adapted to irregular surfaces and shapes.

The Bureau of Ships, U. S. Navy, has investigated the various methods of recording surface conditions to aid in its study of wear and the measurement of surface finish of mechanical parts. This study was given particular emphasis by the Navy's development and test program of main propulsion gearing. During this program, sketches and photographs were made of gear teeth to record surface damage during various test stages. However, the engineers assigned to study the results found the photographs inadequate when a quantitative analysis of wear conditions was attempted. The problem of recording wear on the working surface of the gear teeth under test appeared to be one that could not be solved by use of photographs and sketches alone. The use of a suitable molding medium to produce a three dimensional facsimile of wear was deemed essential. An investigation of existing molding materials such as sulphur-graphite, plaster of Paris, wax, low temperature melting alloys, and others revealed they were unsuited for the work. The search for the three dimensional record finally turned to plastics and the answer was found in a free flowing polyester resin that would harden in ten to twenty minutes after the addition of a catalyst at room temperature without the application of external heat or pressure.

The work conducted in the development of this method is discussed in the following paragraphs.

III. Negative Replica Method.

The study of surface wear was divided into two phases: (a) the analysis of surface finish where a measuring instrument is utilized to determine the roughness and (b) the visual inspection of parts to show where wear has occurred.

The requirements for a plastic molding material were established as follows:

(a) The material must be such that it may be used satisfactorily by comparatively inexperienced personnel in the field.

(b) Equipment must be simple and consist essentially of nothing more than a stirring rod, a small container and acetate tape or similar material.

(c) The plastic should set and cure without the application of external heat or pressure.

(d) Time required between mixing catalyst in resin and removal from surface should be as short as possible.

(e) Reproduction should clearly show surface conditions for visual inspection.

(f) Reproduction of surfaces should be within the limits of accuracy of surface roughness measuring equipment in current use.

(g) The reproduction should be permanent and rugged to permit handling for examination.

A plastic, a polyester resin, that met all the above listed requirements, has been developed.[8] This material is obtainable in preweighed quantities in either a two or three component mix. The two component, resin and catalyst, is packaged in a two compartment container. The three unit mix, resin, catalyst and filler, is packaged in a three compartment container. The two component resin is prepared for casting by squeezing the paste catalyst into the resin and mixing until the materials are well blended. The mix is then poured onto the desired surface. The three component material is prepared by mixing the filler with resin and then adding the catalyst. Weighing and heating equipments are not used with these materials.

Restriction of the plastic to a given area was attempted by constructing dams or retainers of putty, molding clay, paper and other materials. An acetate tape was tested and selected as suitable for building dams for many applications. It was found that this tape was simple to apply, effective in sealing, easy to remove and had no harmful effects on the resulting impression.

IV. Experiments & Results.

The plastics investigated included thermosetting resins that required the application of external heat to cure and also resins that cured by heat generated internally. Early work on small parts was carried out on the former materials and it was possible to place the piece and its plastic casting in an oven to apply heat necessary for the cure. However, this type of material was considered unsatisfactory because it was impractical or inconvenient to apply external heat to large pieces and their plastic impressions. Efforts were then directed toward development of a thermosetting resin that would set and harden at room temperatures without application of external heat or pressures.

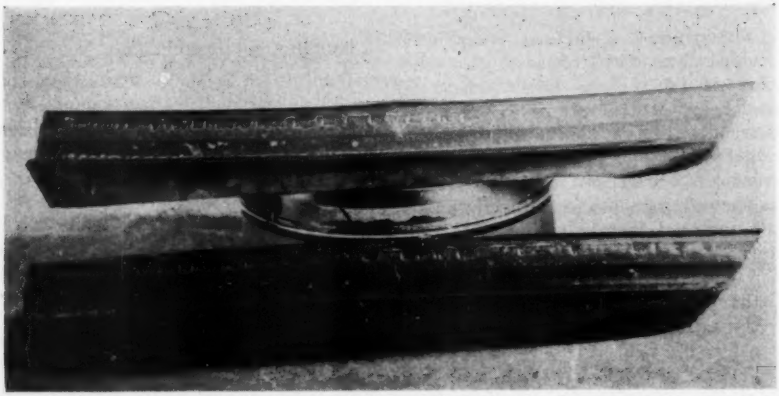


FIG. 1—Impressions of Badly Damaged Helical Gear Teeth. Lower Casting was Distorted by Improper Resin-Catalyst Combination.

Difficulties were encountered during this development. Cracking of impressions resulted from rapid curing. Excessive warping as shown by the lower tooth in Figure 1 was noted in fast curing resin-catalyst combination. These impressions were made on helical teeth and the curvature of the upper casting is an accurate reproduction of the tooth curvature. The lower casting has less curvature, although cast in the same teeth, because of distortion in curing. Bright bubble-like spots (see circled areas) were noted on surfaces of certain resin impressions as in Figure 2. Plastic actually pulled away from surfaces and resulted in poor surface reproduction as indicated (by the arrows) in Figure 2. Imperfect castings were noted where plastic had pulled away from the surface under study before complete jellification and additional liquid resin had then run down into the space between the partially jellified plastic and the work piece. Shelf life of certain resin-filler combinations was not particularly good. Gas pockets were prevalent in surfaces of castings and the surface exposed to air remained sticky for several days unless cleaned with acetone.

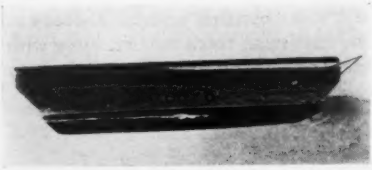


FIG. 2—Faulty Casting of Gear Tooth.

All the difficulties referred to in the preceding paragraph have been overcome. A resin that meets the requirements set forth by the Navy for its reduction gear development program has been obtained and is now available for commercial use.[3]

The following characteristics of this resin are of interest:

(a) The final casting has little or no distortion.

(b) Flaws and cracks are absent in the casting.

(c) Resin run along the side is not encountered.

(d) The casting hardens equally on all surfaces including the air exposed section.

(e) Resin jellifies and hardens in approximately thirty minutes.

(f) All materials are preweighed and can be used in the field by inexperienced personnel.

(g) Weighing and heating equipment are not needed.

(h) Reproduction of surface is good.

(i) Colors can be obtained as desired.

(j) Shelf life of raw materials is approximately two months.

In order to determine the reproductive qualities of various resins a number of castings of resin-filler-catalyst-pigment combinations were produced on a surface roughness comparator plate. Surface finish measurements in microinches (Root mean square) were made with a profilometer of the surface plate and the castings and the results recorded on tapes. A tape record of a plastic casting, made on a surface roughness comparator plate, is shown in Figure 3.

A compilation of surface finish measurements of certain sections of the surface roughness comparator plate and plastic replicas are shown in Figure 4. These measurements were made with the profilometer and tape recorder using a ½ inch stroke on the stylus. The values shown in Figure 4 are averaged from the maximum and minimum recordings on the tapes. It is noted that in the range of 2.9 to 17.4 microinches the maximum variation of the plate and the plastic impression is 0.9 microinches and in the range 33.0 to 70.3 the maximum variation is 4.0 microinches.

The following examples suggest several practical applications for this method of recording surface conditions:

(a) A gear developed signs of surface distress under a series of load tests. In order to permit engineers, located some few hundred miles from the test site, to study the damage, plastic castings were made of the teeth and forwarded to the interested parties. This three dimensional record conveyed more factual information than would have been possible with sketches, photographs and written material.

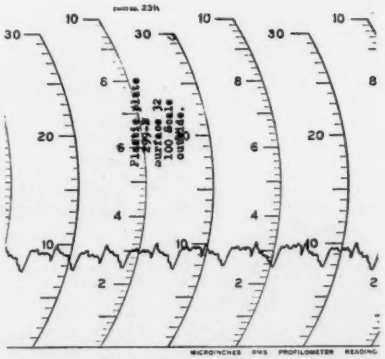


FIG. 3—Profilometer Chart of a Plastic Impression of a Standard Surface Roughness Comparator Plate.

(b) An inspection of boiler tubes indicated pitting inside the tube just beyond the rolled section. Plastic impressions were taken of the inner surface of the tube covering an arc of approximately 120 degrees, at regular intervals over a ten month period. These impressions provided inspectors with a history of the progressive damage to the tube.

(c) During the machining of a condenser flange, it was necessary for a manufacturer to measure the surface finish to determine whether

SURFACE FINISH MEASUREMENTS IN MICROINCHES
(ROOT MEAN SQUARE)

Comparator Block	Negative Replica	Deviation
2.9	2.9	0
6.3	5.4	0.9
7.5	7.5	0
12.7	12.1	0.6
17.4	17.1	0.3
33.0	29.0	4.0
36.5	38.2	1.7
70.3	72.2	1.9

FIG. 4—Profilometer Measurement of Surface Roughness Comparator Blocks and Plastic Impressions.

FIG. 5—Damaged Area of Nitrided Gear Tooth.

the part met the contract specification. A plastic casting was made of the surface in question and the casting was forwarded to a laboratory where equipment was available to determine the finish. The manufacturer and the purchaser's inspector were, in this way, able to determine the finish without transporting the flange to a laboratory or moving the measuring instrument from the laboratory to the shop floor. The plastic casting also provided a permanent record of the machined surface that could be rechecked if necessary.

(d) Several consultants located in widely separated sections of the country were requested to examine the damaged surface of a mechanical part. Plastic castings were made of the surface in question and sent to each of the experts concerned. Then, with the aid of the moulage three dimensional record, they were able to draw conclusions with the expenditure of a minimum amount of time.

(e) An engineer recently commented that he planned to equip his trouble shooters with resin to permit them to make negative replicas of damage to mechanical parts. These replicas would be forwarded to the research department for study.

(f) An organization with many facilities located in remote and relatively inaccessible places should find this three dimensional record of value when studying failures of mechanical elements that cannot be shipped except at great expense.

The procedures for producing a plastic negative replica of a metal surface is simple and no elaborate equipment or painstaking methods are required. The metal surface should be thoroughly cleaned with an approved grease solvent and then with acetone. Suitable dams are constructed to retain the plastic in the desired area. The catalyst is then mixed by hand with the resin (and in certain types of material the filler is also added) and poured on

the area under study. Castings on flat surfaces should be at least 3/8 inch thick. In making castings of irregular surfaces such as a gear tooth the resin should extend at least 3/8 inch above the top of the tooth. The height of resin needed in larger castings will be determined by experience.

An example of a typical application of this method is to record surface damage on a gear tooth as shown in Figure 5. This particular tooth was damaged by an object passing through the mesh. The steps are as follows:

(a) Clean the surface to be studied.

(b) Erect a dam around the distressed tooth, Figure 6.

FIG. 6—Dam of Acetate Tape Erected Around Damaged Tooth to Restrict Resin to Desired Area.

(c) Mix the resin, filler and catalyst and pour into the desired area as in Figures 7 and 8.

(d) Permit the resin to harden, Figure 9.

(e) Remove the dam and lift the casting from the gear teeth. A casting and damaged tooth are shown in Figure 10. Temperature rise of plastic cast in a ten diametral pitch gear is shown in Figure 11.

V. CONCLUSIONS.

The polyester resin as described above has proved to be satisfactory for recording surface conditions where a visual inspection is required. Its use in this application is particularly adapted

FIG. 7—Start of Pour of Resin into Tooth Area.

for development, test and operation of equipment where it is deemed essential to obtain permanent factual records of surface conditions. Progressive pitting of tubes, wear on gears and bearings, erosion of pipes, valves and

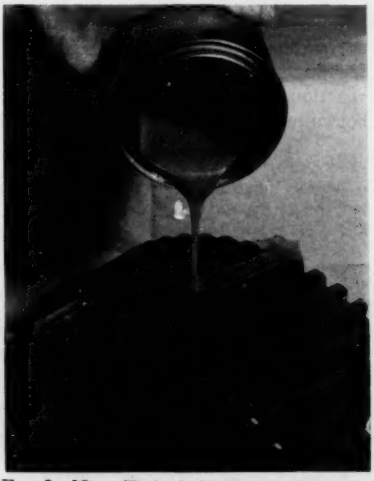


FIG. 8—Near End of the Pour. Note how Resin Covers all Portions of the Exposed Area.

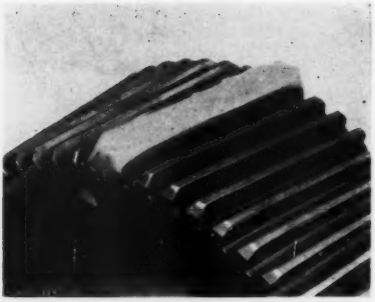


FIG. 9—The Completed Casting with the Dam in Place.

headers, chemical action on machine parts and frictional wear are ideally recorded by this method.

Recording surface finish on production items is readily accomplished. Negative replicas can be made of pieces during shop operations and the replica then taken into the laboratory for the measurement of surface finish and then filed for further study if desired.

The equipment needed to produce a negative replica is not elaborate since the materials are preweighed and curing is carried out by an exothermic reaction. The resin is packaged in a container that is suitable for mixing the resin, filler and catalyst. A small stirring rod, solvent and tape are the other items commonly used. The steps in preparing a dam, mixing the catalyst and the resin, pouring the mix and finally removing the casting can be performed without difficulty. It is considered feasible to produce a complete negative replica of a surface within a thirty minute period after the suitable dams have been arranged.

FIG. 10—The Moulage Record and the Original Surface are Shown for Comparison.

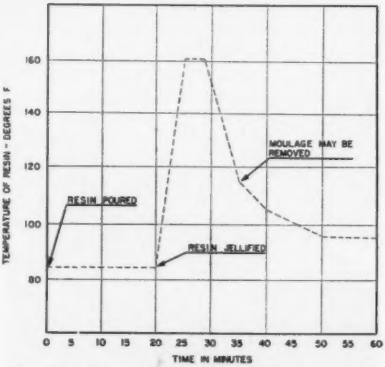


FIG. 11—Time-Temperature Curve of Resin During Curing.

The shelf life of the two component (resin and catalyst) mix is now estimated at two months. It is believed that this time may be greatly extended if the materials are stored at a temperature of approximately 40°F. Tests are now being conducted by the Naval Boiler and Turbine Laboratory, Philadelphia Naval Shipyard to determine shelf life of the two component material. A three component mix (resin, filler, and catalyst) has an estimated shelf life of twelve months. Both the two and three component materials are now available. The resin, filler and catalyst are packaged in a single container with separate compartments. The three component mix has not reproduced surface finish to the same high degree of accuracy as the two

component material. However, for the recording of surface conditions for visual inspection the former material is very satisfactory.

It is recognized that positive reproductions are of great value in certain applications. With this need in view consideration is now being given to the development of a simple and efficient method that will permit production of positive replicas.

The writer wishes to express his sincere appreciation for the splendid cooperation and assistance in this work of Cdr. R. T. Simpson, Mr. H. J. Ball, Mr. A. F. Bird, Mr. C. C. Atkinson, Mr. J. B. Alfers and Mr. J. G. McCubbin of the Bureau of Ships, Navy Department; Mr. J. Cacciola, Mr. S. Weir and Mr. M. Dolan of the Naval Boiler and Turbine Laboratory, Philadelphia Naval Shipyard; Dr. Irving Muskat of Marco Chemicals, Inc. and members of the Navy Gear Industry Committee on Gear Testing.

REFERENCES.

(1) Pearson, J. and M. R. Hopkins: Plastic replicas for surface-finish measurements. Iron and Steel Inst., May, 1948.

(2) Timms, C. and C. A. Scoles: Applications of the plastic replica process to surface-finish measurements. Plastics, Jan. 1949.

(3) Plastic MR-249 was developed for the Bureau of Ships, Department of the Navy by Marco Chemicals, Inc., Sewaren, New Jersey.

Official Photograph U. S. Navy.

DD871 U.S.S. *DAMATO*—DESTROYER.

ROTARY GAS TURBINE COMPRESSORS

Applications for Naval Use—Both Marine and Aircraft

IRWIN E. JACKSON, JR.

THE AUTHOR

IRWIN E. JACKSON, JR. received a B.S. degree in Mechanical Engineering from the Pennsylvania State College in 1934. Prior to his appointment as an engineer in the Bureau of Ships in 1941, he was engaged in public utility valuation and rate regulation, design and construction of transit facilities, and private housing construction. He also served as law clerk in the office of an attorney who was directing the development of a large private housing project. Mr. Jackson completed an M.A. degree in Mathematics at the University of Pennsylvania (1936) and the graduate professional degree of Mechanical Engineer (1941) at the Pennsylvania State College. From 1941 to 1943, he worked on engineering performance analysis in the Research Branch of the Bureau of Ships. Following service as an Air Force engineering officer from 1943 to early 1946, he returned to the Bureau of Ships in his former position. He became a member of the Gas Turbine activity in the Bureau of Ships Technical Division in late 1946, and since that time has been engaged in the development of gas turbine plants for naval applications.

Mr. Jackson has written several Bureau of Ships publications on gas turbines and ship performance. He is a member of Pi Tau Sigma, national honor society in mechanical engineering.

ROTARY GAS TURBINE COMPRESSORS.

Technical and popular accounts of developments in the U. S. in the field of gas turbine engines have been numerous, especially since 1940. Many of these articles have given some space to the consideration of gas turbine compressors as such, but there has been a relative scarcity of material devoted specifically to this component. By comparison the literature on high temperature materials, for example, has reached flood proportions. This disparity in relative volume of literature reflects, to a degree, the

The opinions or assertions contained herein are those of the writer and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service at large.

relative effort devoted to the improvement of high temperature materials as compared with compressors. However, the difference is out of all proportion to the comparative importance of the two in relation to gas turbine development. It is conceded that high temperature alloys, ceramics, and ceramic-coated alloys are in an earlier stage of development than compressors, and therefore offer more promise for the future. Compressors, on the other hand, fall far short of the ideal requirements in many respects. An examination of these ideal requirements for aircraft and naval applications followed by a discussion of the principal characteristics of existing compressor types shows that there are several areas within which further development is needed.

Primary Compressor Function.

The primary function of a gas turbine compressor is to furnish sufficient airflow at the proper thermodynamic conditions over the full desired operating range. This is true whether the application in question is aircraft propulsion, marine propulsion, locomotive drive, power generation, or any other possible gas turbine use. Application considerations affect the number of variables to be taken into account and their relative importance. Aircraft propulsion applications require consideration of altitude and airspeed (ram) effects not present in marine applications. On the other hand, marine applications introduce the requirement of longer service operation in a sea-air atmosphere not involved in aircraft gas turbines. In all gas turbine plants, it is essential that the primary compressor function be performed without excessive power requirements in order to keep the driving turbine size within acceptable limits. Shaft-work engines, such as propeller gas turbines for either aircraft or marine use, place a greater premium on compressor efficiency than the pure jet propulsion machine. The only available output of these units is the net power remaining over the compressor and accessory drive requirements. Such machines produce virtually no useful output with compressors of low efficiency.

Ideal Requirements for Marine and Aircraft Uses.

In order to set up yardsticks which will serve as rough standards of comparison in a discussion of the various existing compressor types, a summary of the ideal characteristics desired in (1) marine and (2) aircraft gas turbine compressors is given as follows:

1—Marine applications

(a) Maximum reliability of operation (10,000-100,000 hrs.)
(b) High efficiency at full load and part load (20% FP).
(c) Broad stability range.
(d) High pressure rise per stage.
(e) Minimum weight and space requirements.
(f) Minimum operating noise level.
(g) Minimum sensitivity to surface deposits.
(h) Minimum sensitivity to vibration and shock.

2—Aircraft applications.

(a) Minimum frontal area.
(b) High efficiency at full load and part load (70% FP).
(c) Minimum weight and space requirements.
(d) Ability to utilize ram effect efficiently.
(e) High pressure rise per stage.
(f) Maximum operating reliability (500-1,000 hrs.)

Current Trends.

Against the background of these ideal requirements, the primary characteristics of the various existing compressor types may now be examined. As indicated by the title, this discussion does not concern itself with

reciprocating compressors. The well-known conventional reciprocating compressor is not suited to employment as a gas turbine plant component, and no attempt has been made to use it in any known development. It is true that free-piston compressors offer considerable promise as gas turbine engine components, but the limits of this discussion will be confined to rotating compressors. Aircraft gas turbine engines utilize axial or centrifugal flow compressors almost exclusively, with a preference for the first type. A combination axial-centrifugal flow compressor was developed by the Bristol Aircraft Company in England for its Theseus gas turbine propeller engine, and some consideration is being given to such a combination unit in this country. The Heinkel-Hirth Company in Germany utilized a combination axial and mixed flow compressor in their 109 series aircraft jet engines, but aerodynamic difficulties were encountered which were never fully overcome. The overwhelming majority of existing aircraft gas turbine engines, however, are built around either axial or centrifugal flow units. Marine gas turbine engineers have exercised more freedom of choice in the selection of compressor types. Axial flow, mixed flow, positive displacement, and centrifugal flow compressors have all been utilized in the plants built under the U. S. Navy program. No preference is yet evident among these types for Naval Marine gas turbine applications, but the only naval unit which has been subjected to sea trials (British "Gatric"-MGB 2009) incorporated an axial flow compressor. Some indication of the future trend may be apparent from the discussion of specific types.

Axial Flow Compressors.

An axial flow compressor is essentially a reaction turbine in reverse. Air flows in a generally axial direction from inlet to outlet undergoing successive changes in direction in transit through alternate stationary and rotating rows of blading. The annular flow passage decreases in area from inlet to outlet to accommodate the diminished volume of air accompanying the increased pressure. Deflection of the air in the direction of rotation produces a change in the tangential velocity component. Diffusion in the blade passages converts the velocity head into pressure rise. An important difference between a reaction turbine and an axial flow compressor is in the nature of the respective flow processes. In a turbine, the flow is accelerating and expanding with decreasing pressure in the direction of flow; while in an axial flow compressor, pressure increases in the direction of flow by deceleration and diffusion. In the first case the pressure gradient tends to stabilize the flow, while in the second case the tendency is toward unstable flow. Since the axial flow path is essentially at a constant radius from the machine axis, no pressurizing effect is obtained through centrifugal force. For this reason, a large number of blade rows is essential for a high pressure ratio, resulting in a long machine. The principal assets of this compressor are its high efficiency and smooth airflow within the stability range. For aircraft applications, its low frontal area is an outstanding advantage and is sometimes of controlling importance. On the other hand, a narrow stability range, high sensitivity to surface deposits, sensitivity to vibration, high initial cost, and fabrication difficulties in forming the blading are liabilities involved in the use of an axial flow compressor. There has been a considerable degree of bias among aircraft propulsion engineers in regard to the selection of gas turbine com-

pressors, which may be explained in part by reference to the historical development of axial flow and centrifugal flow machines. Disregarding these preconceived notions, the axial flow unit merits a superior rating for aircraft use on its low frontal area and high efficiency at the present state of compressor development. For marine applications this compressor is in a less favorable position. Sea trials of the British MGB 2009 indicated the presence of a serious compressor blade fouling problem due to operation in sea air, with a consequential decrease in efficiency.

Centrifugal Compressors.

A centrifugal compressor consists of a rotating impeller and a stationary casing into which diffuser passages are built to convert the velocity head of the air leaving the impeller into pressure. Air enters the impeller in a generally axial direction and leaves in a radial direction, passing through radial diffuser passages. Centrifugal force imparts a velocity head to the air and a partial conversion of velocity head into pressure is obtained within the impeller passages. Most of the pressure rise occurs in the diffuser, and the proportional division between the rotating and stationary elements is a function of the impeller speed. Since the total pressure rise is divided between the impeller and diffuser, both impeller and diffuser performance affect the overall compressor performance. Simplicity of construction, relative insensitivity to surface deposits, increased stability range, and lower cost are the principal assets of centrifugal compressors. A decreased efficiency offsets these good points to an extent which depends largely on the intended application, since lower efficiency means increased power requirements and increased driving turbine size. The simplicity and rugged construction of this compressor are its most important favorable qualities. Fabrication problems are thereby simplified, manufacturing time is decreased, and operating reliability is increased. Surface deposits do not affect the performance of a centrifugal compressor to a noticeable degree, so far as is now known. The superior overall characteristics of this compressor make it attractive as a marine gas turbine engine component where efficiency and economy are not primary considerations. For aircraft applications, the large frontal area of a centrifugal compressor is a liability which may be of controlling importance.

Mixed Flow Compressors.

These compressors are characterized by impeller flow passages which utilize both axial and radial pressurizing forces. Diffuser passages similar to those used in centrifugal compressors are incorporated in mixed flow units. An example of this type of compressor is the Birmann wheel manufactured by the DeLaval Steam Turbine Company. There is little descriptive literature available concerning mixed flow compressors but test results show that the performance characteristics of these machines lie between those of axial flow and centrifugal compressors, approaching the latter more closely. A variety of impeller shapes is possible within this classification and several different experimental designs have been built and tested. The Birmann compressor is the only mixed flow type in the United States which has passed the experimental stage. In addition to the attributes stated above mixed flow compressors are characterized by efficiencies comparable to those of centrifugal compressors, relative insensitivity to surface deposits, and performance characteristics dependent primarily upon impeller shape.

Lysholm Compressors.

A Lysholm compressor is a rotary positive-displacement machine in which air entering through intake ports in the casing inlet end passes through the clearance spaces between male and female helical rotors connected by timing gears, and leaves through exhaust ports in the casing outlet end. These clearance spaces between the lobes of the male rotor and the grooves of the female rotor are so designed that the air trapped in the clearance space by the movement of the rotors in covering the intake ports is compressed before the exhaust ports are uncovered. Compression in this machine is not a backflow effect but a consequence of the location of the inlet and exhaust ports. The principal assets of the Lysholm compressor are its practically unlimited stability range, its decreased sensitivity to surface deposits, and its good efficiency (lower than axial flow but higher than centrifugal and mixed flow types). On the other hand, a characteristic low rotative speed, high noise level, increased cost, high specific weight, and limited stage pressure rise are disadvantages which have prevented the wide adoption of this machine as a gas turbine plant component. A wide range of stable flow and relatively flat efficiency curves are the best points of advantage for Lysholm compressors. These characteristics lead to excellent part load operation and the maintenance of acceptable plant efficiencies over a wide range of operating conditions. Rotative speed limitations imposed by the nature of this machine make it essentially a slow speed unit. Therefore, the driving turbine must be geared to allow high turbine speed or the number of turbine stages must be increased if the turbine is direct-connected. In either case a penalty is incurred in weight and space. Lysholm compressors are not suited to aircraft gas turbine use and no serious effort has been made to utilize them for such applications. For marine applications the good part-load qualities of these compressors are very attractive, but the high operating noise level associated with the non-steady flow process is a definite tactical disadvantage. Maximum sound intensities of high magnitude have been recorded on tests of uninsulated Lysholm compressors. Although a considerable noise reduction is obtainable by the use of properly designed inlet and outlet silencers together with insulation of the compressor and duct work, an overall evaluation of Lysholm compressors shows severe limitations on their general adaptability to naval marine service.

Compressor Performance.

An accurate evaluation of a machinery component involves the interpretation of performance data. Since all relevant factors cannot be quantitatively measured, the performance data alone do not fully solve the evaluation problem. Mechanical simplicity and operating reliability, for example are not quantitatively measurable in the same sense as efficiency. Performance measurements do serve as a convenient basis of comparison although other factors may be controlling in the final analysis. Standardization of methods of representing compressor test results has not yet reached the stage of universal acceptance, but progress is being made. A basic graph which has found wide acceptance in the United States is the so-called performance map on which pressure ratio is plotted as the Y-axis with flow rate as the X-axis. Contours of constant adiabatic efficiency and lines of constant speed are shown on the basic grid. Pressure ratio (p) is usually the ratio of the absolute discharge and inlet total

pressures. Flow rate (Q or W) may be shown as inlet flow volume (cfm), mass flow rate (lbs/sec), or percentage of rated flow. The values may be actual measured values or corrected quantities reflecting a conversion to standard inlet conditions of temperature and pressure. Percentage of rated speed is sometimes used in place of actual measured rpm or a corrected speed converted to standard inlet conditions. It is possible to further generalize the variables used in describing compressor performance according to the principles of dimensional analysis to include the effect of variation in size and in cycle fluid thermodynamic properties. The prevailing practice does not follow these abstractions farther than a correction for variation in inlet conditions. Compressor performance is easily summarized on a performance map and the surge line marking the limiting pressure ratio and flow for each speed is shown clearly. The position of the operating line established by a compressor and its driving turbine may be shown on the map, thus affording an estimate of the margin of safe operation under the surge limit as well as the degree of success obtained in matching the compressor and turbine.

Since an unbalanced condition of operation may prevent the attainment of rated power output, especially where the compression or expansion occurs in steps, the importance of adequate matching is evident. It is also essential, in successful matching, that the power requirements of the compressor be accurately known. A separate graph showing power required (HP) as the Y-Axis against pressure ratio or flow rate as the X-axis is usually shown with a series of constant-speed lines which may be correlated with the performance map. Consideration of the turbine characteristics, compressor data, and the conditions for operating equilibrium provide a satisfactory solution to the matching problem.

Current practice in reporting compressor performance makes use of several other graphs. One showing adiabatic efficiency versus pressure ratio at constant speed is commonly used. Another showing adiabatic temperature rise or the ratio of adiabatic temperature rise to initial temperature against pressure ratio at constant speed is frequently used. Modifications of the previous graphs showing mass flow instead of pressure ratio are also used. The performance map is the best overall representation of compressor operating characteristics though the other graphs mentioned above may be useful in specific instances. Together with the graph of power requirements the map completely establishes the quantitative performance of any compressor.

Reynolds number and Mach number are important limiting factors in compressor performance, especially for aircraft applications. Extreme variations in inlet atmospheric conditions and flight speeds characteristic of modern aircraft operation require a determination of Reynolds and Mach effects. For marine applications, these effects are much less marked. Definitions of Reynolds number (Re) and Mach number (M) are

$M = V/A$

where A = velocity of sound in fluid

[for air, $A = 49.2\sqrt{T}$ (T = air temperature, °F. abs.)]

V = mean velocity of fluid relative to blade

$Re = VD/\gamma = VD\rho/\mu$

where V = mean velocity of fluid relative to blade

D = blade chord length

γ = kinematic viscosity $= \mu/\rho$ = abs. viscosity/density

Mach number is an index of the shock or compressibility effects produced by high speed fluid flow. As the gas velocity approaches that of sound the flow pattern breaks down due to the formation of shock waves and the efficiency of the blading falls off. Since the distribution of air velocities along the blade profile is not uniform, Mach effects are noticeable below M=1 (sonic velocity) based on mean air velocity due to the local shock waves formed at points on the blade profile where the local fluid velocity approaches that of sound. Recent investigations on axial flow compressors for the production of high stage pressure ratios indicate an increase in the importance of Mach number. Reynolds number is an index of scale effect (i.e. size) which is customarily used to indicate points or regions of flow transition. A scale model and a full-size machine or machine element are dynamically similar if the corresponding Reynolds numbers are the same. Reynolds number represents the ratio of inertia forces to viscosity forces. Low Re values correspond to high viscosity forces and high Re values denote high inertia forces. The most important consequence of this factor in compressor performance is that extremely low Reynolds numbers are associated with unstable flow and low efficiency. For axial flow compressors a lower limit of Re = 100,000 based on blade chord has been established. A further consequence is that for small capacities (flow rates) the axial flow compressor apparently loses its efficiency advantage over the other compressor types. Operating experience on axial flow compressors indicates that the blade height of the last stage imposes a serious limitation on capacity in addition to that imposed by the ratio of the first stage blade height to its diameter. The first limitation is a Reynolds number effect. The blade chord is related to the blade height through the aspect ratio which may only be varied within narrow limits imposed by end losses, rate of turning losses, and mechanical rigidity requirements. Since the low aspect ratios corresponding to low blade

1—Marine Applications.

Item	*Axial*	*Centrifugal*	*Mixed-Flow*	*Lysholm*
Adiabatic Efficiency	A	C	C	B
Stability Range	C	B	B	A
Cost	B	A	B	C
Operating Reliability	B	A	B	B
Noise Level	A	A	B	C
Insensitivity to Surface Film	C	A	A	B
Vibration	B	A	B	C
Mechanical Simplicity	C	A	B	D

2—Aircraft Applications.

Item	*Axial*	*Centrifugal*
Adiabatic Efficiency	A	B
Frontal Area	A	C
Weight	B	A
Operating Reliability	B	A

Notes

A = Excellent
B = Good
C = Fair
D = Poor

heights denote large blade chords and relatively long flow paths, the combination of low Reynolds number and low aspect ratio maximizes the friction losses and end losses leading to low efficiencies. These considerations are not necessarily conclusive against the use of axial flow compressors in small sizes, but the simplicity, reliability, and lower cost of centrifugal compressors are more attractive in this capacity range where the efficiencies of the two types are comparable.

Suggested Rating Chart.

The charts on page 835 are suggested as a rough basis for rating the various compressor types. Only relative ratings are used, and there is no correlation between rows (items).

Conclusion.

In the foregoing discussion, an attempt has been made to survey the existing machinery under the classification of rotary gas turbine compressors, and to point out the assets and liabilities of specific types. Consideration of the special requirements of marine and aircraft applications has shown that further development work is necessary to close the gap between desired characteristics and available characteristics. The impression that existing rotary compressors are sadly lacking in development should be avoided. On the contrary, the significant improvement in gas turbine component characteristics coupled with the development of suitable high temperature materials during recent years have been primarily responsible for the current success of this prime mover. It is nevertheless necessary that the process of ironing out the salient disadvantages of the various types of rotary compressors be undertaken in order to consolidate the initial foothold of gas turbines in the field.

MANAGEMENT ENGINEERING

Its Historical Development and the Naval Shore Establishment

REAR ADMIRAL MILTON CARLSON, U. S. N., RET.

THE AUTHOR

Graduated U.S.N.A. 1916; turret officer U.S.S. *Utah* in World War I. Postgraduate in Ordnance (torpedoes) serving afloat in destroyers, light and heavy cruisers and battleships in gunnery duties. Commander U.S.S. *Simpson* and U.S.S. *Charleston*. Ordnance Superintendent Navy Yard, N. Y., Jan. 1941 to February 1944 during time of greatest expansion. Subsequently commanded Attack Transport Divisions and Transport Squadron 13 in Western and Southwest Pacific. Naval Commission to India-Burma-Malay States. Commanded Torpedo Station Newport when retired at own request in June 1947.

The following paper was presented to the Logistics Class of the Naval War College as a study of certain factors and problems with which industrial management is involved in the change-over from peace to war time operations. It was delivered in support of the general subject then under study by that class—namely "The Capabilities of the Shore Establishments to Support Fleet Mobilization".

The word "management" is derived from the Latin "manus" or hand—and from that basic significance comes the derivation in meaning to handle, to direct, to guide, to conduct and finally to control. The history of management literally follows that change in meaning. Time does not permit its development in this paper—suffice it to say for our purposes, that industrial management had its birth when the crafts came out of the kitchens in the homes of the workers and were housed in separate buildings. Here, where two or more persons plied their trade as cobblers, smiths, weavers or tailors, industrial management was born.

The owner-manager of these early establishments was the master of his craft—he owned the tools. He was, in truth also the master of his help—for they were for the most part his sons or younger kinfolk, or persons bound to him in apprenticeship. Management was then as simple and direct as the organization was elementary.

Management took its first infantile steps toward its modern role when the

*The opinions expressed herein are the author's and are not necessarily supported by the Navy Department.

owner manager, or the manager put in charge by the patron (and that word is used in its original, if archaic meaning) discovered that his organization became more effective as he divorced himself from hand work to direct his help and conduct more carefully the phases of his business external to the shop; in short, when he ceased to "handle" and began to "control". The manager really became a manager when he left off using his hands and began to use his head. From these modest beginnings developed the present role of management, or the part that it plays in modern industry.

The role of management in modern industry is, briefly:

1. to conceive and build the organization
2. to sustain it in operation
3. to perpetuate it by planning its future operations.

The function of management in building an organization is to furnish the basic knowledge and enterprise; in operation, to furnish technical and financial direction; and in planning, to furnish the imagination or vision, and the confidence, based on a well considered projection into the future, of accurate data on past and present performance. While management is furnishing these factors, it must constantly bear in mind the

1. interests of the owners,
2. the effect on labor and labor's reaction to present operations and to prospective changes in those operations, and
3. the possible demands of present and prospective customers.

These three groups, the investors, labor, and the customers, and satisfying their demands which, incidently, are not always compatible, are the constant concern of the modern manager, standing as he does, between the owners of the tools, on the one hand, and the users of the tools, and the users of the product, on the other.

When one spoke of management in the not distant past, he meant the owner-manager, the financier (the modern patron), the Board of Directors, or the "topside-management" in the front office. The gap between that topside management and labor was filled with an almost lethargic medium of persons not quite labor, and still not quite manager known in the shops as "bosses".

They were in a sense lost souls, master craftsmen not directly engaged in their crafts, fulfilling a necessary function that management itself could not fulfill, and accepted by labor as a necessary evil which they could not avoid. As modern industry developed and changed, so the concept of management has also changed until this intermediate group has in that same sense found its soul as it has slowly but surely been incorporated into the body of management.

Management in its modern concept is the term, then applied to the whole body of managers of an organization. We are not now concerned with the owner manager shop, though much of the matter will apply to it equally, as well as to a large establishment employing hundreds or thousands of people. In such an organization there may be many managers in many echelons. From top man to lowest supervisor as long as they hold executive positions, they are all managers.

In the hierarchy of such management, there is the man at the top, the president; under him, vice presidents or heads of department for planning, design, production, procurement, sales, advertising; in the third echelon: shop superintendents, maintenance superintendents, transportation superintendents, etc.; in the fourth echelon: shop masters; in the fifth: foremen; in the sixth, quartermen; in the seventh: leadingmen; and in the eighth echelon: "snappers" or "straw bosses." Each of these if he has executive authority is a man-

ager. Each heads an organization, progressively smaller, it is true, as one proceeds down through the echelons, but nonetheless an organization. Each has the common task of thinking ahead of those who report to him; of helping and guiding his subordinates in their work toward the common goal of the organization, and of reviewing the work of his subordinates to ensure that their output meets the requirements of his immediate superior.

But this ideal organization, where it exists, did not just happen. It took a good deal of building. In fact, looking at industry as a whole, it is even now in the process of building and like so many intangibles, it seems necessary to arrive at it by indirection rather than by a direct route. It is in a sense a by-product of an effort called scientific management which was, incidently, not initially directed at management at all, but at labor.

As industry developed and grew, the relations between the owners and workers became less personal. The upper brackets of management becoming more and more involved in the external affairs of their company, eventually knew less and less of internal operations and techniques until these were left almost entirely in the hands of subordinate supervisors and the men at the machines. The same widening breech changed the attitudes of the workers, as well; instead of selling their talents to their employers, they began to sell their time. Psychologically, there is a great difference between these two: when a man sells his talents, time is of no great import; when he sells his time, some outside incentive must be applied to bring out his talents. From recognition of this difference, and out of that concept grew what later became known as scientific management.

The first exponent of scientific management in this country was one Frederick Winslow Taylor. The scientific management movement was as much his brain child, and its successes those he himself fostered, that its history is best told as the story of his life, the greater part of which was devoted to the improvement of American industry. Taylor came from a moderately well-to-do Philadelphia family. His father intended him for law, to which end he was entered at Exeter in preparation for Harvard. At Exeter he stood one in his class. The strain of study, however, affected his eyes and he had to leave school. While recuperating, he took a job at a small machine shop near home. Here he completed an apprenticeship in pattern making, and then another as machinist. Looking for wider fields of experience, he then took a job at Midvale Steel Company. This was during a nation wide business slump, and the best job he could get as a starter, was that of yard laborer (1898). In due course, he was fleeted up to the machine shop, in which eventually he became foreman (1891). His rise had been rapid; he was still in his late twenties.

Having come up through the ranks he was well acquainted with his men and quite familiar with their point of view. He knew by actual experience, for instance, that in the shops, the output of the machines was restricted by the workers; that "soldiering" on the job was common and considered normal; and that all past attempts by management to speed up work had been met by a quiet but stubborn resistance on the part of the men.

This had disturbed him throughout his association with industry, and as he thought about it, he came to the conclusion that it stemmed from two principal factors:

1. sheer laziness on the part of the inferior or unambitious
2. Unwillingness to extend themselves on the part of the others, since there was no incentive to raise the output or improve the work. There

were other factors, of course, but the system which he devised as foreman to get increased production was a direct attack on these two. That system he came later to call scientific management.

First, he cleaned up his shop and improved working conditions generally. Second, he standardized the tools of his workers and installed a central tool issue room. Third he speeded up the machines. Fourth he determined by stop watch observation and by calculation, *scientifically* the best method of doing repetitive work and the time it should take to do it. This time he called the standard rate. Fifth, he got authority from the topside management to pay incentive wage rates, and finally, after overcoming a good deal of suspicion and opposition in the shop, he persuaded his men to work toward this standard rate.

In short—he standardized working conditions
—then set a high rate of work as a goal for each day for each man
—he rewarded those who made this goal with a materially increased price per piece
—he penalized those who failed to meet the standard rate by paying them a lower price per piece.

His system worked—and was installed in all shops at Midvale Steel (by this time he had been promoted to Shop Superintendent). At one and the same time he had raised his men's wages and increased the company's profits. Scientific management was off to a good start. Taylor published his work —others took it up, some learning under him, others independently.

Scientific management was met with approval by a good number of engineers and industrialists. It was not, however, popular in the shops. When, for instance, it was introduced into the foundry at Watertown Arsenal in 1911, it brought on a strike of molders. As a result of political pressure by labor leaders a Congressional Committee subsequently investigated the system's merits and demerits. The chief results of that investigation are two:

1. a mass of conflicting testimony —3 thick volumes
2. inclusion, thereafter, in the War and Navy Department appropriation bills of a provision banning the use of stop watches or any other measuring device for gauging the output of individual workmen — and banning the payment of incentive wage.

That incident marked the end of wage incentives in the military and naval industrial establishments, and with this end came a temporary setback to the scientific management movement not only in these plants but also in private industry.

It is only fair to say that Taylor's difficulties in selling his ideas were not only with the men. He had his battles with management too, from top to bottom. From the top, came objections to raising the pay of men above the prevailing wage rates in the area. These objections were silenced—but not forgotten—when increased profits began to appear. Taylor had continuously to fight a tendency to cut the piece rate. From among his contemporaries and colleagues in the organization came protests, as the even tenor of their way was disturbed. They called him an impractical idealist, a crack pot reformer and a radical. His own subordinate supervisors almost invariably objected to these new fangled techniques and had to be sold the ideas, and held into line individually. The labor leaders called him a slave driver. The way of the reformer is hard. Fortunately for Taylor, he was capable of being pretty tough himself.

So the Taylor system was not, in the end, altogether a success, except where

he personally had charge, and then only as long as he stayed in charge.

Failures in these early attempts to improve production were due to three principal factors

1. from trying to sow the seed in ground that had not been properly prepared.
2. from the faulty primary assumption that most if not all the blame for unsatisfactory production lay at the door of labor, and
3. except as practiced by Taylor himself, they gave scant attention to the human element at the machine.

Scientific management has changed a good deal since Taylor first published his ideas in the 1880's. It has also taken on a new name Industrial Engineering. Its greatest contribution to national industry has been to call attention to the constant need for examination and improvement of procedures and techniques. It finds its greatest effectiveness when it is actively supported by all echelons of management. As a matter of fact—without such support in any establishment, it is foredoomed to failure.

And that is what is meant by saying that the early failures were due in part to being sowed in a field not properly cultivated. It also explains Taylor's successes. Taylor sold his ideas down all the echelons of management as well as he could—where he couldn't sell the idea and get support, he supplied it in his own person. There is ample evidence to show he realized that before the attitude of the man on the machine, can be changed toward his work—the attitude of the lowest supervisor must be changed. This lowest supervisor must understand the intention of management, the whys and hows of prospective changes in procedures or techniques; must be convinced that a change is necessary, and that it can be accomplished without harm to himself or his colleagues. He must feel that he is in the confidence of management (his superiors). He must feel that their interest and his coincide. In short, he must be made to want the change. If possible he should be put in the position where he can suggest it—or at least, have such a large part in its planning that he identifies it with his own interest. He must be made to feel that he is management.

Just that is the essence of management engineering—the welding of management into one cohesive, sympathetic body, the managing or contriving to make management work.

Whereas scientific management or industrial engineering is concerned with the conditioning of labor and adapting the tools of labor so as to get the most out of them, management engineering is the indoctrination and training of management so as to get the most out of it. The first deals with the artisan and the handling of his tools; the second deals with the leader and the handling of his men. They are both, proper tasks of management, and the success of the first, depends on the soundness of the second.

The military services have long recognized the need for special indoctrination and training of junior and petty or non-commissioned officers. From the beginning of Big Business, top men have applied themselves consciously or unconsciously to the development of subordinate leaders. But it is only within the last 25 years that realistic campaigns directed toward this end have been carried out in industry. Some leaders in this field are:

Bell Telephone Co.
General Electric Co.
Westinghouse Electric Co.
General Motors Inc.

all of which prescribe courses of study for their subordinate managers (junior executives). Within the last year, articles have appeared in the press indicating that the Ford Motor Co. and Standard Oil Co. have also embarked on such programs.

Within the last two years the Navy Department has directed similar training programs for its civilian supervisory force, by requiring them to take part in what is termed a Work Improvement Program. This is not to say that management engineering in some form or other has not previously been practiced at our shore establishments —but this is the first time that the Navy Department has emphasized the need and made training not only formal but a pre-requisite to promotion in the supervisory force.

The Naval Shore Establishments include industrial organizations which compare favorably in size with some of the largest civilian concerns in the country. Under management control of the Bureau of Ships are the shipyards; under Bureau of Aeronautics, the aircraft factory; under Bureau Supplies and Accounts, the clothing factory; under Bureau of Ordnance, the gun-factory, powder factory, torpedo stations, etc.

The functions and mechanics of management in those shore establishments are not materially different from those in private industries. But there are some very real differences in the managements themselves. The first difference is the presence of naval officers with their relatively short tenures of office, in the upper echelons. The second difference derives from the civil service status and background of the supervisory force.

With the exception of E.D.O's, few officers assigned duty in those shore establishments grow up, step-by-step in industrial management. Many come direct from billets at sea, and without previous training are placed in responsible positions where they are required to give not only administrative but also technical directives to persons who have made administration and these techniques their life's work. Not infrequently the officer is placed, administratively over a person, older, more experienced and more highly paid than himself. This in itself would not be too bad, if the best fitted officers were always selected for the jobs. Too frequently this is not the case. These are situations rarely found in private industry.

Marked as is the first difference between private and naval management, it is not as striking as the second. The vesting of technical responsibility in the military command, definitely precludes even the exceptional civil service administrator from rising to the topmost rung of the ladder in naval industrial establishments. Except temporarily and in the absence of the regular officer, he, the civilian supervisor can hardly aspire to the status of a superintendent, much less to a department head. There is a very definite ceiling, therefore, in his prospects of promotion. There is, to counterbalance this ceiling, a security both of tenure and promotion up to this ceiling within the civil service system that has no counterpart in private industry.

This is not a proper time to evaluate the merits or demerits of such a system. Suffice it to say that because of its civil service status and background, and because of its permanence in the establishment as compared with the short tours of duty of the officer managers, the civilian supervisory force forms a definite managerial group within the industrial system, different from the officer group in the upper two or three echelons—and different from the corresponding group in private industry.

The Navy then, in its management Engineering must deal not only with the ordinary supervisor problem common to it and to civilian industry, but also with this special factor peculiar to its kind of organization

The Naval Shore Establishments differ in another way from private concerns. During times of peace their employment is low and their jobs are few. While they may have many repeti-

tive jobs, each is, comparatively speaking a small job, and in most cases in the nature of repairs to existing equipment, or the manufacture of spare parts for the same. New jobs are scarce, and much sought after. They are usually of "pilot model" nature, where a small number of units of new equipment are made for test by forces at sea. Mass production procedures in any of the foregoing illustrations are rarely economical. The Shore Establishments management—and the workers, therefore, get used to "job lotting". On the other hand, in private establishments of size comparable with our Shore Establishments, orders which cannot be processed by mass production procedures are taken only with reluctance. Such plants normally have not only the tools but the personnel available and trained to that type of procedure. They must be used in a way which brings the maximum return—the companies must make a profit or go out of business. So while the modern private plant of any size is constantly geared for high production procedures, even when its output is at low ebb—the contrary is true of Naval Shore Establishments. If stepped-up production is wanted (as for instance when *M-day arrives*), private industry has only to increase its labor force, provide more machines, and if need be, offer incentive wage to get that wanted production. In the Naval Shore Establishment it would appear that the first task is to re-orient the present man power. This task is not merely to get them to "double time"—to work faster —for which incidently no wage incentive may be offered, but what is much more difficult, to accept if not a scientifically developed mass production procedure, at least a properly planned production procedure in their shops. It would not, at first glance, seem difficult to convince the workmen of such need and change over to it especially under the stress of war.

Actually, it involves, for a material percentage of the workmen, all the personal difficulties of habit breaking and new habit forming. A machinist, for instance, accustomed under job lot procedures to work for a few days on a lathe, then possibly shift to a shaper, then to a boring mill, or to assembly, rarely finds the routine of his work tiresome. He takes a new stance with each job; there are new immediate surroundings, both material and men; there are new problems. He doesn't have time to get bored. Among other factors, and by no means the least important to him, he feels that he is maintaining his skill in the operation of *all* the tools of his trade. He likes these changes, and in that atmosphere develops a particular feeling for his routine, a habit of mind.

It is not only the artisan who develops a feeling for job-lotting: the supervisors as well fall into a simple routine. Since the number of units to be made are few, there is no need for long range planning. There are normally few complicated preparations to be made for the work. With alert artisans at the machines, and short term jobs, close supervision is almost unnecessary. Eventually, they grow content to see that a reasonable amount of reasonably good work is turned out and delivered where the boss wants it. It is not true to say that a shop organized for job lotting is on its way to spending more and more time doing less and less—but it is true to say that a shop so organized can only with difficulty be converted into one where the *natural* tendency will be to produce more and more.

When, in such a shop the need for stepped-up production arises, job-lotting as such must be reduced to a minimum and mass production or at least planned production procedures instituted. Under these conditions the artisan may find himself stuck at one machine (presumably the one he is best fitted to operate) for months on end. To get the

most out of that machine he may be told what rates of feed and speed and what tools he should use; he may be told that with those rates and tools, it is possible to produce so many units per shift and that it is necessary to produce them so that an even, planned flow of materials through the shop will bring these to assembly at the right time—so that the final product may be supplied the customer at the required rate. To you and to me these would appear to be perfectly proper directives. The artisan may recognize them as such and still resent them because he is not habituated to them. Though he may realize the necessity, he is almost bound to feel that they restrict the freedom of action he enjoyed under the other conditions; he won't like it.

Now the supervisor—he really has to begin thinking ahead of his men, interpreting instruction (route) cards; assigning and equalizing machine work loads and planning the routing of work through his part of the plant. He has to make preparations to supply the tool needs, the oiling and overhaul schedules for his equipment, and all the other little jobs that the men did for themselves when the pressure was light and they could leave their machines. And he has to keep the pressure on so as to get the scheduled output. He will have new hands, possibly unskilled, at least unfamiliar with the plant, who will require close supervision—and he will have to work on the old men who are now standing up to the same machine day after day month on end with interest dulled by the unvaried routine. These will require moral support, and he is the proper person to supply it. He too may quite realize the need for the change without liking it. And he is the important link in the chain, the one at the bend, the link that goes over the sheave and gets the most chafing in the heaving and hauling that seems inevitable in the relations between management and labor. This man is the real target in naval industrial management engineering. The way he holds up during and after change over from job lotting to mass production procedures will largely govern the reaction of the men who work under him. The way he holds up will depend largely on how well he has been trained in his managerial duties and how well he has been indoctrinated in the views of management.

Management Engineering cannot reach this lowest supervisor overnight, nor in a week or even a month. It must slowly work down through all the echelons of the supervisory force. The foundation for this man's managership is on top of him, not under him; and that foundation must be well prepared by training and indoctrination before these can be turned on him. Once he is reached that training and indoctrination must be continuous—and it must be good; it must be inspiring, convincing, and technically useful. He is the key man. This is the process used in the Work Improvement Program as set up by the Navy Department.

There is a good reason to believe that conscientiously carried out this program will materially strengthen the organization of the Shore Establishments—so that they will be better prepared to shift from peace to wartime operations —and so be in better case to support fleet mobilization.

ION EXCHANGERS

Their Naval Application

HARRY FLEISHER

THE AUTHOR

MR. FLEISHER serves as Chemical Engineer in charge of the Chemicals Section of the Research Division of the Bureau of Ships. He received his PhG degree from the Philadelphia College of Pharmacy and Science in 1931, and served for fifteen years in government employment, which included eight years as Plant Chemist at the Federal Central Heating Plant in Washington. His present Navy Department position includes the direction of research investigations on industrial chemicals and their shipboard application.

INTRODUCTION

"Water, water, everywhere,
Nor any drop to drink."

These resounding words of the Ancient Mariner, depicting the terrifying ordeal of the stranded sailor, are quite archaic in our present day Navy. No longer does the threat of tortuous death from thirst on a becalmed sea exist, as it did in the days dramatized by Coleridge.

From time immemorial, the search for practicable and efficient methods of producing fresh water from sea water has been paramount among the many problems of Naval strategy. But science, as it has done with so many other seemingly insurmountable problems has finally produced the solution.

Modern distilling plants, operating in multiple-units of great efficiency and yield, provide plentiful supplies of drinking water, as well as fresh water for other purposes, regardless of the ship's location or the length of the voyage. As for the sailor forced to abandon his ship at sea, a much more recent development, the ion exchanger, created by the never tiring minds of the chemists, produces palatable water from sea water in ample quantities to sustain life.

Perhaps, the ghosts of the Ancient Mariner and his illfated shipmates would gasp in awe if they could witness a seaman on a life-raft taking a drink of water right out of the ocean!

In recent months, there have been directed to the Bureau of Ships a flood of civilian inquiries regarding the Navy's magic chemical which possesses

the power of converting sea water to fresh water, and its possible application to the production of large quantities of water for irrigation purposes. As will be evident in the following discussion, these inquiries are the result of gross misunderstanding of the purpose and scope of these new chemicals.

In hopes of dispelling this misunderstanding, and casting light on the principles and limits of ion exchange materials, this discussion is devoted.

Shortage of Natural Water Supplies

A bill recently introduced in the House of Representatives (HR 5777) provides for the inauguration of an intensive and exhaustive research and development program to overcome the alarming decrease in the nation's supply of ground water. A national crisis has been created by the growing shortage of water for everyday needs. Singularly selected as a potential means for overcoming this threat to the national economy and welfare is the proposition of converting sea water into water suitable for irrigation purposes.

Several methods have been proposed for accomplishing this objective, prime among which is the method of distillation using high capacity vapor-compression stills very similar to those units used for years by our Naval vessels, but of comparatively gigantic size.

Another method has also been proposed—the method of ion exchange. To attempt to reason that ion exchangers can be used to convert sea water into fresh water is much too premature at the present time, because the most efficient ion exchangers available today cannot practicably demineralize water containing more than 1000 parts per million of total solids. Sea water, containing roughly 40,000 parts per million of dissolved salts, tops this limit by 40 times. Moreover, it costs $0.05 to demineralize 1,000 gallons of water containing 100 parts per million of total solids. If a suitable exchanger were available today for the concentrations encountered in sea water (and it isn't), it would mean a cost of $20.00 for every 1000 gallons of fresh water produced—an intolerably excessive cost.

Yet, as new exchangers of higher capacities, better stability, and greater versatility are created, and improved techniques developed, one would be lacking in vision if he did not recognize the potentialities of this new tool. The development of ion exchangers of the resin type is a recent one. Small commercial applications are already in operation and are serving to provide information leading to larger scale uses. Continued studies and field tests are broadening the knowledge of exchange materials and their application.

Definition of Ions

In order to understand the phenomena of ion exchange and how it works, it is essential that we know the meaning of the ion, its purpose and its function in chemical reactions and formation of chemical compounds.

All matter is made up of small particles of mass called atoms. Atoms combine with other atoms to form molecules of a chemical substance. An atom may be pictured as a tiny solar system in which electrons revolve with tremendous speeds (like planets) around a heavy nucleus. The electrons carry a negative electrical charge—the nucleus a positive charge. Gener-

ally the entire system of an atom is in complete electrical balance only when it is combined with another atom to form a molecule. Thus, a molecule like sodium chloride (NaCl), or common table salt, containing one atom of sodium (Na) and one atom of chlorine (Cl), is in perfect balance with respect to electrical charge. On dissolving in water, this sodium chloride splits up into its respective sodium atom and chlorine atom, each atom existing as an individual particle of matter. As a result of this splitting, the sodium atom loses electrons and hence becomes positively charged—the chlorine atom gains electrons and hence becomes negatively charged. If, however, the water is removed by evaporation and the salt subsequently recrystallized, the atoms again join together, there is an exchange of the lost and gained electrons, and a molecule of neutral charge is again produced. These charged atoms which form when certain chemical substances (electrolytes) are dissolved in water, are what we refer to as *ions.*

Thus, we see that ions are extremely minute particles carrying an electrical charge of positive or negative nature. The positive ions are denoted with a plus mark, such as sodium (Na^+), and the negative ions with a minus mark, such as chlorine (Cl^-). Negative ions form acids in combination with hydrogen, and salts in combination with metallic ions. The positive ions are generally those of hydrogen and the metals.

All positive and negative ions combine with each other in definitely established ratios. Thus, we have the positive ions hydrogen (H^+), sodium (Na^+), calcium (Ca^{++}), magnesium (Mg^{++}), aluminum (Al^{+++}), iron (Fe^{+++}), etc., combining with the negative ions hydroxyl (OH^-), chloine (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{--}), sulfate (SO_4^{--}), phosphate (PO_4^{---}), etc., to form acids, bases and salts, in strict accordance with an inherent combining power peculiar to each individual ion. This combining power of ions is known as *valence.* Hydrogen (H^+), a monovalent positive ion, combines with one atom of chlorine (Cl^-), a monovalent negative ion, to form a molecule of hydrochloric acid (HCl). Calcium (Ca^{++}), a divalent positive ion, combines with two chlorine ions (Cl^-) (Cl^-) to form a molecule of calcium chloride ($CaCl_2$), or with one sulfate ion (SO_4^{--}) to form one molecule of calcium sulfate ($CaSO_4$). Aluminum (Al^{+++}), trivalent and positive, requires three chlorine atoms (Cl^-) (Cl^-)(Cl^-) to form a molecule of aluminum chloride $AlCl_3$. And so on with every element in the atomic system.

When acids, bases and salts are dissolved in water, some or all of their molecules split into positive and negative ions. These ions wander about in the solution, and recombine, redissociate, and recombine again at great speeds. (Incidentally, the word "ion" is derived from the Greek word "ienai" which means to wander, which is precisely what these little particles do in water), If two electrodes carrying electricity were to be placed in a solution of electrolytes, the dissociated ions would migrate to the pole carrying the charge opposite to the charge carried by the ion itself. The positively charged ions would migrate to the negative pole, the cathode, and are therefore called *cations.* The negatively charged ions would move to the positive pole, the anode, and are therefore called *anions.* This migration of ions is the old familiar process of *electrolysis.* Upon arriving at the anode, the chloride ion (Cl^-) gives up its extra electrons, thus balancing the ionic charge of its solar system of nucleus and electrons. Since no sodium is around to combine with the chloride (the sodium ions have migrated to the cathode), the chloride ions combine with them-

selves to form chlorine gas (Cl_2) having no electrical charge. In the absence of an electric current, the charged anions and cations will continue to wander in an aimless fashion like fish in a pond.

Some chemical compounds, like sugar and alcohol, do not dissociate into ions when dissolved in water. These materials are referred to as non-electrolytes, and are immune to ion exchangers.

Theoretical Aspects of Ion Exchange

Ion exchange is accomplished through the use of ion exchange materials which have the property of reacting with certain ions in liquid solutions with which they come in contact. These materials are insoluble, complex mineral or organic substances. The process of ion exchange is a reversible one involving the "swap" of one ion from the exchange material for an equivalent amount of ions in the solution. There is always an even exchange—never a lost ion, never one gained. The process requires intimate contact between solution and exchange material, and usually results in the removal of an undesirable ion from the solution. The exchange bed retains this unwanted ion until some later time when it can be removed from the exchange bed by reversing the ion exchange reaction.

Since ion exchange materials are extremely complex compounds, they show extremely complex reactions. The mechanism of ion exchange has been thoroughly investigated by many workers, and many significant contributions have been made. Ion exchange phenomena involve many physico-chemical functions, including the Law of Mass Action, ion diffusion, reaction rates, and other phenomena much too complex to include in this elementary discussion. Whether the process is that of true adsorption or of a reaction within the exchanger interstices is still unestablished. Kunin (1) explains simply that the exchange material itself might be considered as completely dissociated —that is, composed of dissociated ions, not undissociated molecules. The active surface ions on the exchange material may be considered as being bound to the exchanger lattice with a lower binding energy than those of the internal ions which do not take part in the exchange of ions. When placed in a polar solution, these surface ions become solvated, a further lowering of their binding energy results, and a marked dissociation from the lattice takes place. If a foreign electrolyte is added to the system, it is logical to expect an exchange to take place between these surface ions and ions of the same charge in the foreign electrolyte. The extent of this exchange will depend upon: 1) the force which binds the active ion to the exchange lattice, 2) the relative valence of the ions involved, 3) the total concentration of ions in the solution and in the exchanger (Law of Mass Action), 4) the size of the ions, and many other factors beyond the scope of this explanation. Kunin found that the exchange affinity of an exchanger molecule for a particular ion in solution increased with an increase in valence of the ion being absorbed. Hence, it was found that the following order of selectivity existed between the cations as listed, showing that cations of higher valence are more easily retained by an exchanger bed than ions of lower valence:

$$Th^{++++} > Al^{+++} > Ca^{++} > Na^{+}$$
$$\text{Thorium} > \text{Aluminum} > \text{Calcium} > \text{Sodium}$$

It was also found that cations of higher atomic weight (or number) are more easily retained:

	Cs^+	>	Rb^+	>	K^+	>	Na^+
	Cesium	>	Rubidium	>	Potassium	>	Sodium
Atomic No.	55		37		19		11

Similar effects were noted in the alkali earth series:

	Ba^{++}	>	Sr^{++}	>	Ca^{++}	>	Mg^{++}
	Barium	>	Strontium	>	Calcium	>	Magnesium
Atomic No.	56		38		20		12

The Law of Mass Action will reverse the order of selectivity if the concentration of the ion of lower selectivity is greater than that of the ion of higher selectivity.

Exchange Capacity

The ability of an exchange material to adsorb ions is expressed as *exchange capacity*, defined as the weight of ions which one unit volume of the material will adsorb. This is usually measured in milliequivalents of ions adsorbed per cubic centimeter of exchange material, or in grains per cubic foot. Capacity is sometimes expressed as the total amount of water hardness which a unit volume of exchanger will adsorb. Exchange capacity differs for each ion exchange material, and for each type of ion adsorbed. Other factors which affect the exchange capacity are of complex nature, but are mentioned merely to warn the unwary that exchanger capacity generally refers to one certain condition, against one certain ion, and at one certain concentration. To assume that capacity applies to all possible conditions is erroneous and will inevitably result in misapplication. Of similar importance is the fact that if a particular ion exchange material is known to have twice as much exchange capacity as another ion exchange material, it does not necessarily follow that the volume of the exchange bed may be reduced proportionately. More than often it is wiser to permit the bed size to remain the same, thereby allowing the bed to purify twice the amount of water before regenerating.

Exhaustion and Breakthrough

When an exchange bed has released all the ions in its molecular structure for ions adsorbed from the treated solution, it is considered *exhausted*, and passage of more water through the bed will result in no further change. Shortly prior to exhaustion the bed will begin to miss a few ions as the water passes through, and these "missed" ions appear unchanged in the effluent water. This missing of ions is known as *breakthrough*, and is usually determined by analytical tests to determine the presence and amount of missed ions. In most exchangers, breakthrough begins to occur when 75-80%

of the exchange capacity has been reached. Then breakthrough begins at first at a slow rate, rapidly increasing as more ions are adsorbed, until finally showing a very sharp break at the point of total exhaustion. Of course, it is obvious that breakthrough will be affected somewhat by the size of the exchanger granules and the flow rates of the water being softened. When an exchanger bed is exhausted it is not necessary to discard and replace the bed. It can be revived easily by a procedure known as *regeneration*. However, before discussing the process of regeneration, it is appropriate that the phenomenon of *leakage* be explained, since this is so often mistaken for *breakthrough*.

Leakage

It is often common practice to operate ion exchangers at reduced regenerant levels in order to achieve economy. Obviously, when an exchanger is under-regenerated, a certain percentage of influent ions will pass through the exchanger unaffected. The degree with which these ions pass through the system depends upon a number of factors of which ion charge and size predominate, as was explained under "Theoretical Aspects of Ion Exchange". It has already been shown that equilibrium relationships between an exchanger and an electrolyte solution are such that monovalent ions are held much more loosely than are those of higher valences. Consequently, monovalent ions are not only more difficult to remove completely from the solution, but are also the first to appear at the breakthrough point. This passage of ions because of the effect of ionic charge or size, is known as *leakage*, and will often be confused in practice as *breakthrough*.

Regeneration

Regeneration of an exhausted bed is accomplished by reversing the exchange reaction in order to remove the adsorbed ions from the bed lattice and restore the active surface ions to their original place in the lattice structure. This restores the bed to its original receptive condition. Regeneration is accomplished by treating the exhausted bed with a concentrated solution of the ion which it has given up in the exchange reaction. Thus the Law of Mass Action plays an important role in the regenerating cycle. In the softening cycle where the calcium ions predominate, the reaction proceeds as a softening process. By increasing the sodium ion concentration, the process is reversed because the sodium ions are then predominant. In regenerating a softener exchanger, the calcium and magnesium ions adsorbed from the hard water are released from the exchange bed, and the regenerant solution containing the dissolved calcium and magnesium ions is flushed to the sewer or drain as it flows from the exchanger. Regeneration usually requires 30-60 minutes, depending upon the type of material involved. It is usually accomplished with a flow direction opposite to the exchange flow direction, so that the exchange particle which last contacted the water will be the first to be contacted by the regenerant and thus more completely converted. Regeneration usually requires about 200 percent of the theoretical equivalent quantity of regenerating chemical calculated from the exchange capacity. The higher the exchange capacity, the more the regenerating chemical that must be used. It also follows that a higher concentration will be required.

Backwashing

Backwashing is the process of passing water through an exchange bed in a flow direction opposite to the flow of liquid during the exchange period. Backwash serves to loosen the bed and rearrange the particles. The particles are reclassified hydraulically with respect to particle size, the larger particles on the bottom. This improves operating characteristics, eliminates channeling, and reduces the tendency toward packing, which inevitably results in excessive pressure drops. Backwashing also helps remove from the bed any foreign matter which was filtered or precipitated from the influent water. During the exchange period fine particles collect near the bottom of the exchanger and clog up the screen, thus causing dangerous pressure drops. Backwashing removes these particles from their position, and causes them to resettle into a new pattern. Usual practice calls for a backwash just prior to regenerating, at a flow rate sufficient to expand the bed 50%. Generally the amount of water required is 5-7 gallons per minute for each square foot of bed.

Backwashing must also follow regeneration even though the bed was backwashed prior to regeneration. This wash removes the excess regenerating chemicals and serves to again reclassify the bed and wash the bed particles. In new installations, it is good practice to backwash the bed before starting the exchange flow, because new exchange materials contain small amounts of fines which must be removed to avoid excessive resistance to flow and clogging of screens.

An exchange cycle is the total process of exhausting and regenerating an exchanger bed. This includes both backwashing and washing. Since backwashing may not scrub the particles sufficiently to dislodge encrusted and suspended contaminants, a bed is often *bumped* to remove these foreign substances which derive from turbid waters, or waters polluted with oil or organic waste. Bumping consists of completely draining the exchanger unit and then admitting backwash water in the form of a violent surge so as to agitate the particles. Sometimes surface wash sprays, similar to those used in sand filters, are used in place of bumping.

Exchange Materials

The ion exchangers are divided into two principal classes, the cation and the anion (more correctly acid) exchangers. The *cation exchangers* are those which remove cations from solutions, and are operated in either the sodium cycle or the hydrogen cycle.

Sodium cycle exchangers are generally employed to remove calcium and magnesium from water, as in the softening of water for boiler or laundry use. The exchange occurs when sodium ions are released from the exchanger matrix and replaced with calcium and magnesium ions contained in the water being treated. The reaction is shown as follows:*

$$\underset{\text{Calcium bicarbonate}}{Ca(HCO_3)_2} + \underset{\text{Sodium X}}{Na_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Sodium bicarbonate}}{2NaHCO_3}$$

$$\underset{\text{Calcium sulfate}}{CaSO_4} + \underset{\text{Sodium X}}{Na_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Sodium sulfate}}{Na_2SO_4}$$

*Note "X" will be shown as the symbol for all cation exchanges.

$$\underset{\text{Calcium chloride}}{CaCl_2} + \underset{\text{Sodium X}}{Na_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Sodium chloride}}{2NaCl}$$

$$\underset{\text{Calcium nitrate}}{Ca(NO_3)_2} + \underset{\text{Sodium X}}{Na_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Sodium nitrate}}{2NaNO_3}$$

In regenerating a sodium cycle exchanger, a concentrated solution of sodium ion, usually in the form of brine, is used. The reaction is shown as follows:

$$\underset{\text{Calcium X}}{CaX} + \underset{\text{Sodium chloride}}{2NaCl} \leftrightarrow \underset{\text{Sodium X}}{Na_2X} + \underset{\text{Calcium chloride}}{CaCl_2} + NaCl \text{ (excess)}$$

Hydrogen cycle cation exchangers remove sodium ions as well as calcium and magnesium ions. The exchange involves the release of hydrogen ions from the bed in exchange for calcium, magnesium, and sodium ions in the water. The exchanged ions occupy the position in the exchange lattice formerly occupied by the hydrogen. Acids are produced in the process and certain of these acids, such as carbonic, sulfurous, and hydrogen sulfide, are released by aeration or heating. When all the hydrogen ions in the lattice have been removed, and their spaces filled with metallic ions, the bed is exhausted. The exchange reaction is shown as follows:

$$\underset{\text{Calcium bicarbonate}}{Ca(HCO_3)_2} + \underset{\text{Hydrogen X}}{H_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Carbonic acid}}{2H_2CO_3}$$

$$\underset{\text{Calcium sulfate}}{CaSO_4} + \underset{\text{Hydrogen X}}{H_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Sulfuric acid}}{H_2SO_4}$$

$$\underset{\text{Calcium chloride}}{CaCl_2} + \underset{\text{Hydrogen X}}{H_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Hydrochloric acid}}{2HCl}$$

$$\underset{\text{Calcium nitrate}}{Ca(NO_3)_2} + \underset{\text{Hydrogen X}}{H_2X} \leftrightarrow \underset{\text{Calcium X}}{CaX} + \underset{\text{Nitric acid}}{2HNO_3}$$

$$\underset{\text{Sodium chloride}}{2NaCl} + \underset{\text{Hydrogen X}}{H_2X} \leftrightarrow \underset{\text{Sodium X}}{Na_2X} + \underset{\text{Hydrochloric acid}}{2HCl}$$

In regenerating a hydrogen cycle cation exchanger, a concentrated solution of hydrogen ions, usually in the form of an inorganic acid, is used. The regenerating reaction is shown as follows:

$$\underset{\text{Calcium X}}{CaX} + \underset{\text{Sulfuric acid}}{H_2SO_4} \leftrightarrow \underset{\text{Hydrogen X}}{H_2X} + \underset{\text{Calcium sulfate}}{CaSO_4}$$

$$\underset{\text{Calcium X}}{CaX} + \underset{\text{Hydrochloric acid}}{2HCl} \leftrightarrow \underset{\text{Hydrogen X}}{H_2X} + \underset{\text{Calcium chloride}}{CaCl_2}$$

In backwashing a hydrogen cycle cation exchanger, distilled water is required because raw water high in calcium and magnesium forms insoluble calcium carbonate and magnesium hydroxide which coat the bed, and clog the pores of the exchange lattice. For the same reason, hydrochloric acid is preferred to sulfuric acid for regenerating, because calcium salts, in the presence of sulfuric acid, form slightly soluble calcium sulfate precipitates which block and exhaust the exchange groups in the exchange bed. Moreover, presence of insoluble calcium salts on the exchange bed will cause undesirable calcium leakage during the exchange cycle.

Anion exchangers are not really exchangers, but true adsorbers. They have the characteristic of being able to adsorb whole molecules (not ions) of acid on the surface of the exchange particle. In this way, they differ from the cation exchanger, which exchanges ions within its own molecular structure. The adsorbed acid in an anion exchanger reaction does not become a part of the molecular structure of the exchange particle. Nevertheless, the term, *anion exchangers,* has found general acceptance, despite the fact that these materials are really adsorbers of acid molecules, not ions. They are usually employed in conjunction with hydrogen cycle cation exchangers to remove the acids formed by the latter. When the hydrogen cycle cation exchanger is exhausted, the anion exchanger will no longer be effective since it can adsorb only the acids produced by the first pass through the cation exchanger. Of course, there may be acids naturally present in the water before softening, and in this application the anion exchangers serve to remove them. It should be apparent to the reader that the process may also serve for the recovery of acid, if so desired.

The combination of a hydrogen cation exchanger and an anion exchanger will accomplish the complete removal of all ions from raw water, thus resulting in a product which, for all practical purposes, is equal to distilled water. This is commonly termed *demineralization.* The raw water is fed to the top of the cation exchanger tank, flows down through the bed, and out the bottom. It then flows to the top of the anion exchanger bed, through the bed, and out the bottom. Acids formed in the cation bed are removed by the anion exchanger. Demineralization may also be accomplished by combining sodium and hydrogen exchangers. Often zero hardness is purposely avoided so as to leave some residual hardness by which to maintain a corrosion balance. To do this, only a part of the raw water is demineralized. The cost of demineralizing water is relatively high, and, where only hardness is encountered in the water, is not considered desirable, nor necessary. This is especially true where high concentrations of chlorides and sulfates are present in the water. Careful studies of the economics involved may prove sodium cycle processes more desirable than the demineralization process.

The anion exchange reaction is shown as follows:(*)

$$\underset{\text{Hydrochloric acid}}{2HCl} + \underset{\text{Anion X}}{X_a} \leftrightarrow \underset{\text{Anion X} \cdot \text{Hydrochloric acid}}{X_a \cdot 2HCl}$$

$$\underset{\text{Sulfuric acid}}{H_2SO_4} + \underset{\text{Anion X}}{X_a} \leftrightarrow \underset{\text{Anion X} \cdot \text{Sulfuric acid}}{X_a \cdot H_2SO_4}$$

*Note "X_a" will be shown as the symbol for all anion exchangers.

Regeneration of the anion exchangers is usually accomplished with strong alkali solution, usually sodium hydroxide or sodium carbonate (the latter is preferred because it is easier to wash out of the bed thus requiring less wash water);

$$\underset{\text{Anion X · Hydrochloric acid}}{X_a \cdot 2HCl} + \underset{\text{Sodium carbonate}}{Na_2CO_3} \leftrightarrow \underset{\text{Anion X}}{X_a} + \underset{\text{Sodium chloride}}{2NaCl} + \underset{\text{Water}}{H_2O} + \underset{\text{Carbon dioxide}}{CO_2}$$

$$\underset{\text{Anion X · Hydrochloric acid}}{X_a \cdot 2HCl} + \underset{\text{Sodium hydroxide}}{NaOH} \leftrightarrow \underset{\text{Anion X}}{X_a} + \underset{\text{Sodium chloride}}{NaCl} + \underset{\text{Water}}{H_2O}$$

It has been known that anion exchangers will show preferential adsorption for one kind of acid over another—for example, sulfuric over hydrochloric. Even after the exchange capacity has been exceeded, the bed will adsorb sulfuric acid at the expense of hydrochloric acid, as shown in the following reaction:

$$\underset{\text{Sulfuric acid}}{H_2SO_4} + \underset{\text{Anion X · Hydrochloric acid}}{X_a \cdot 2HCl} \leftrightarrow \underset{\text{Anion X · Sulfuric Acid}}{X_a \cdot H_2SO_4} + \underset{\text{Hydrochloric acid}}{2HCl}$$

Note: For the sake of simple clarification, the explanation of ion exchangers and principles has been applied to the process of water softening. While this application is perhaps the most important, there exist many other applications of great importance, but which are too complex to use in this discussion.

Why Exchange Ions

We have explained ion exchange principles and how ion exchangers function. The question now arises—"Why remove these ions?" The answer to this question may be found in the following story about water and its purpose in industry and the home.

Natural water is never found in nature as a pure compound. It never exists as pure H_2O. It always contains impurities, dissolved or suspended, which are normally leached from the land which the water drains. In nature, water is a solution of many, many impurities of varying concentration and composition. These impurities must be removed if the water is to be used for industrial or personal purposes. Suspended solids, including vegetable debris and particles of silt and bacteria, are removed by coagulation, sedimentation, and filtration in the municipal water treating plants. Gases are often malodorous and may cause corrosion

in equipment. Their removal is accomplished by processes of aeration and deaeration. Tastes and odors are eliminated by passing the water over beds of activated carbon which adsorb the contaminants. After all these treatments, the water may be fit to drink, but is still far from pure because none of these processes remove the dissolved salts. In many industries and processes these salts must be removed. Calcium and magnesium, iron and manganese, in water will produce boiler scale, reduce the lathering power of soap, form tenacious curds of soap in the laundry, produce unsightly stains on laundered clothes, and introduce undesirable tastes, color, and appearances in food products. Many industries are affected. The chicken industry is a good example, though not a strictly technical one. To remove a fowl's feathers, hot water is used. If the water contains calcium in appreciable quantity, the feathers are set so tightly that much time and effort is spent in dressing the fowl, and, more important, the appearance of the final product is far from pleasing. The removal of calcium from the wash water facilitates the removal process. Similarly, in the sugar industry, soft water is essential to the production of refined sugar. Sugar is crystallized by evaporation of large quantities of water. If excessive salts are present, not only will the final product be deleteriously affected, but the process itself becomes less efficient and operating costs are increased due to the heat insulating characteristics of scale formed in the crystallizing vats.

History and Types of Ion Exchangers

As was shown above, there are two general types of ion exchangers, the cation and the anion exchangers, identifying the type of ion which an exchanger will remove from solution. The cation exchangers are grouped into four general classes, descriptive of the chemical nature of the material itself. They are the naturally occurring zeolites, the synthetically prepared zeolites, the carbonaceous "zeolites", and finally the resinous ion exchangers. The anion exchangers (better described as acid adsorbers) are of but one type, the amine-formaldehyde resin type, although some dolomite and heavy metal silicates occuring in nature have been found to exhibit some acid adsorption characteristics.

The history of ion exchangers dates back about 100 years. In 1850, the existence of cationic clays was first discovered by Way (2), as an important factor in providing food and minerals from the soil to the plants. Later it was found that montmorillonite, zeolite, glauconite, and the chabazites possessed greater capacity than the clays originally discovered by Way. Still later some additional work was done on kaolinite and feldspar. In 1928, organic exchangers were introduced (3) in the form of carbonaceous "zeolites", produced by the sulfonation of coal with fuming sulfuric acid. (The term "zeolite" had become so deep-rooted, that it was applied generally to all ion exchange materials even though of organic nature).

Ion exchange resins were first synthesized in 1935 by Adams and Holmes (4) in some original work conducted at the Department of Scientific Industrial Research, in London. The first resins produced in this country were those of the Resinous Products and Chemicals Corporation, under a Commercial license to the Adams patent (5). Although the original work of Adams and Holmes was limited more

or less to water treatment, applications to other industrial and laboratory processes have since expanded to gigantic proportions, particularly in the last few years. The first cation exchange resin produced in this country was *Amberlite IR-1*—the first anion type, *Amberlite IR-3*.

Zeolites (or green sand because of their characteristic green color) occur naturally and are mined. They are insoluble hydrous silicates of iron, aluminum and sodium, and look like ordinary sand. Their exchange capacity is usually of a low order, approximately 2,500 to 5,000 grains of calcium carbonate per cubic foot. They are regenerated with sodium chloride in concentrated solution. Regeneration usually takes about 5-15 minutes. The main use of zeolites is for softening water supplies, particularly for boiler consumption. Calcium and magnesium ions in the water being treated are exchanged for sodium ions. Iron salts, occuring naturally in water supplies, will poison a zeolite bed, and should be removed prior to softening. A typical commercial zeolite is *Zeo-Dur*, a natural glauconite. The advantages of zeolite softening is evident in the fact that all the hardness is removed. The zeolites are simple to use. They will form no insoluble sludges (as in the case of lime-soda softeners) to be later disposed of as waste. The disadvantages of zeolites include low capacity and instability to acids and alkalies, as well as high temperatures. They will give up silica if the water being treated is low in silica. They will cause severe pitting due to the disturbance of the calcium balance and produce increased alkalinity in the water, particularly if the waters contain high concentrations of bicarbonates. Bicarbonates are converted to carbon dioxide in a steaming boiler, and should be reduced to a minimum in order to avoid corrosion of condensate return lines. Zeolites also increase total solid content of treated water since two sodium ions are substituted for one calcium ion or magnesium ion in the water. Cost factors should always be considered in selecting a zeolite softener for a particular purpose. Often it will be found that lime-soda softening will be more economical, especially if the water is high in bicarbonate hardness.

The synthetic zeolites are mineral zeolites made from desiccated aluminosilica gels. They are characteristically white in color. Like the natural zeolites they are regenerated with sodium chloride. Processing of natural zeolites by means of high temperature increases the porosity of the zeolite and increases the exchange capacity. The capacity is usually about 6000 to 12000 grains of calcium carbonate per cubic foot. The advantages and disadvantages of the synthetic zeolites are essentially the same as those of the untreated zeolites, except for the higher adsorption capacity. Regeneration with sodium chloride requires 3.5 pounds of NaCl for every pound of hardness exchanged. *Super Zeo-Dur* and *Decalso* are two of the more popular commercial synthetic zeolites.

Carbonaceous zeolites are carbon base materials of complex organic structure. They are black in color, and are produced by sulfonation of coal or lignite. The principal feature of these materials is stability to acids and alkalies. They may be regenerated with either salt or mineral acids so as to provide either the hydrogen or the sodium cycle. Treatment with acid provides available hydrogen which converts all the salt radicals of the removed cations into the corresponding acids. Total solids of the effluent water are decreased. Bicarbonates are converted into carbonic acid, which readily decomposes into water and carbon dioxide, and is removed in a degasifier, a spray tower similar to a baffled cooling tower. The exchange capacity of the carbonaceous zeolites ranges in the

order of 6000 to 12000 grains of calcium carbonate per cubic foot, which is about the same as treated mineral zeolites. Organic leaching from carbonaceous zeolites is negligible. Their disadvantages are similar to those given for the mineral zeolites, except that they are operative in alkaline or acid waters. The principal commercial products are *Zeo-Karb, Catex, Nalcite MX,* and *Organite.*

The cationic resin exchangers are synthetic phenol-formaldehyde polymers or hydrocarbon type resins, in which the active exchange ion is the highly ionized sulfonic acid or carboxylic acid group. This active group is usually attached to the aromatic nucleus of the resin lattice. Many of the resin exchangers are available in spherical bead form which greatly minimizes resistance to flow and possibility of channeling. They are high molecular weight polyacids of high capacity, good chemical stability, and wide application to a great number of electrolytes. They are easily adaptable to the sodium or hydrogen cycle, by regenerating with salt or mineral acids, respectively. All the resin exchangers are shipped in fully swollen condition, wetted with distilled water to about 35-50% of their weight. If shipped dry, the resins will expand upon wetting—sometimes as much as 25%—and burst shipping containers. Most of the cation exchange resins are available in grain size of 20-50 mesh and are shipped in sodium form. To convert to the hydrogen form, it is necessary to treat the material with two successive regenerations and rinses using ½ the acid concentration required for exhaustion regeneration. Of the commercial cationic resins, the most well-known include *Ionac C-200, Ionac C-284, Duolite C-1, C-2* and *C-3, Zeo-Rex, Dowex-50,* and the *Amberlites.* The *Amberlites* will be treated in detail.

Amberlite IRC-50 is furnished in the hydrogen form, as white opaque beads having an apparent density of 40-45 pounds per cubic foot. It has an active carboxylic acid group which classifies it as a weakly acid exchanger. Of high capacity (20,000 to 100,000 grains per cubic foot), it shows selective action for copper even in the presence of calcium and sodium. It is regenerated with dilute mineral acid, preferably hydrochloric. It serves a very useful purpose in the treatment of acid sensitive systems, such as in removing salts from milk.

In the sulfonic acid group resins, the adsorbed ions are held so strongly that very large volumes of regenerating acid are required in order to displace the exchanged ions. In fact, the efficiency of acid as a regenerant is so low that many ion exchange applications have been found impracticable for large scale operation. *Amberlite IRC-50* contains a loosely bound carboxylic acid group which helps overcome this objectionable characteristic of the sulfonic acid type of resin.

Amberlite IR-100 is furnished in the sodium form, as irregular black granules, having an apparent density of 37-38 pounds per cubic foot. It has an active sulfonic acid group which classifies it as a strong acid exchanger. Of relatively low capacity (7,000 grains of calcium carbonate per cubic foot), it is regenerated with mineral acid.

Amberlite IR-105 is furnished in the sodium form as spherical beads, having an apparent density of 47 pounds per cubic foot. Except for a higher capacity (14,000 grains of calcium carbonate per cubic foot), it is essentially identical to *Amberlite IR-100.*

Amberlite IR-120 is similar to Amberlite IR-105, except for a very high capacity of 28,000 grains of calcium carbonate per cubic foot. It has excellent resistance to attrition and high temperatures, and has excellent chemical stability. Tests have shown that the material will not show any capacity

change after 750 cycles of regeneration and exchange.

The anion resin exchangers are amine-formaldehyde products. As in the case of the cation materials, they are shipped in moist, fully swollen condition, and are available in the same grain size. The best known commercial anion exchangers are *Ionac A-300, De-Acidite, Amberlite IR-4B, Amberlite IRA-400,* and *Amberlite XE-75.* All are regenerated with sodium hydroxide or sodium carbonate.

Amberlite IR-4B is furnished in sodium form as irregular granules having an apparent density of 32 pounds per cubic foot. It possesses an exchange capacity of 25,000 grains per cubic foot for hydrochloric acid, and 30,000 grains per cubic foot for sulfuric acid. It is considered a weakly basic material.

Amberlite IRA-400 is furnished in the sodium form in light brown spherical beads. It is heavier than *Amberlite IR-4B,* having an apparent density of 42 pounds per cubic foot. Although it has a lower exchange capacity than IR-4B, it has a much more rapid exchange rate, requiring only 30 seconds to reach equilibrium. It is a strongly basic material and is capable of removing weak acids such as silicic, boric and carbonic acids. It is useful in the removal of silica from water, and is used in conjunction with deionizers for demineralization, the IRA-400 constituting the last pass.

Amberlite XE-75 is a highly porous, strongly basic anion exchange material supplied as the chloride in light amber bead form. It has a density of 46 pounds per cubic foot, and is regenerated with 4% sodium hydroxide followed by 10% sodium chloride. It is being utilized in the pharmaceutical manufacturing industry, particularly in the purification of penicillin.

Exchanger Equipment

The equipment used in an ion exchanger is that required to house the exchange material, to guide the water through it, and to provide for regeneration and backwashing. The exchanger is usually a vertical cylindrical pressure tank much like an ordinary sand filter tank. The bottom of the exchanger is provided with suitable screening and a bed of graded gravel, usually consisting of quartz, with which to support the exchanger material. The gravel is graded with the coarser particles at the bottom. Most units have distribution piping at the top and bottom to insure that the water passes uniformly through the bed. The units are provided with inlets and outlets for untreated and treated water, backwash water, regenerating solution, and rinse water; meters and flow controls, underdrainage systems, and tanks for regenerant solution storage. The size of the bed depends upon the exchange capacity of the material, the hardness of the water, and the amount of water to be softened between regenerations. The higher the exchange capacity, the less the weight and size of the unit required, or, if the unit size is not reduced, the greater the volume of water which may be softened before regeneration. Beds are usually 30 to 75 inches deep. The deeper the bed the less amount of wash water required for the amount of water softened. Some units operate on an automatic control arrangement, but the majority are either semi-automatic or manually controlled. Most exchanger beds are provided with a single multiport valve to control the softening and regenerating phases.

Flow rates are often 5 to 6 gallons per minute for each square foot of bed. Generally the flow rate is of the order of 0.3 volumes per minute for the exchange phase, 6 to 10 volumes per hour

for regeneration, and 10 to 20 volumes per hour for washing, all based upon the volume of the exchanger bed. Standard practice calls for downflow operation because minute particles of exchange material are filtered out in passing through the granules of the bed. This may be due to the tendency of downflow to bring the particles together, whereas upflow causes the particles to separate from each other. Where flow rates are fluctuating, downflow is usually recommended. Upflow operation is used where steady flow rates are occasioned, or where the viscosity of the liquid is so high that excessive pressure drops would be incurred in downflow operation. Upflow operation shows greater leakage through the exchanger run, but shows a more gradual breakthrough than in downflow operation.

Ion exchange equipment must be constructed of materials which will resist the action of acids and alkalies. This is not only to protect the equipment, but also to maintain the purity of the treated water. There must be sufficient freeboard between the top of the bed and the upper distributor to allow for bed expansion during backwashing. Usually about 18 to 24 inches is a minimum.

Industrial Applications

Although ion exchange principles have been known for almost a century, it has only been in recent years that their utility has broadened into a wide variety of commercial applications and uses. When they first appeared they were used chiefly in the purification of water for specific purposes. Since then their utility has grown without limit. Even today, with much work yet to be done, their industrial applications are legion. Much has been published regarding their successful use in the brewing industry, the ice manufacturing industry, the food processing industry, paper mills, textile mills, and a host of others. Some successful applications include the following:

(a) Removal of metallic contaminants from sugar solutions

(b) Recovery of copper, zinc, and chromium from plating baths

(c) Recovery of large quantities of silver nitrate, chloroplatinic acid, and uranyl acetate used extensively in chemical laboratories

(d) Demineralization of photographic wash waters

(e) Recovery of large quantities of photographic fixing solutions (utilizing an anion exchanger which removes the silver as a thiosulfate complex)

(f) Recovery of valuable organic materials such as pectin from citrus and wine wastes, nicotine from tobacco, and cinchona from the bark.

(g) Destruction of organic peroxides in hydrocarbon liquids

(h) Removal of acidity from petroleum products using a dry resin having an exchange capacity of approximately 3.0 moles of lower aliphatic acids per liter

(i) Radioactive decontamination

(j) Separation, concentration, and purification of the radioactive isotopes—in order to evaluate the radiotoxicological effects of atomic fission byproducts, it was necessary to quantitatively separate each of the radioactive isotopes. It was recognized that atomic fission products consisted primarily of the isotopes of the rare earths, but their separation had baffled chemists for many years. Through the use of resinous exchange materials, the separations were effected, and much information was gained about the behavior of ion exchange materials in the sequence of adsorbability for the rare earth metals, as reported by Kettele and Boyd (6).

Naval Applications and Experimental Work

Much research and development in Naval laboratories have been directed toward determining the utility of ion exchange materials in certain Naval applications. In some of the applications investigated, it was determined that ion exchange was not warranted, while in others favorable results were reported and ion exchangers have since been adopted for particular applications. Ion exchangers are now providing softened water for many Naval establishments ashore, for use in laundries, boilers, and dishwashing. Shipboard applications include the purification of battery water, and desalination of sea water for life raft casualites. Investigations incidental to other potential shipboard uses include the partial softening of evaporator feed, and the removal of residual salts from boiler feed water. They are discussed later.

Battery water purification—Submarine distilling plants, producing water for batteries and portable use, are constructed of monel metal, as are the storage tanks in which the distilled water is stored for eventual use. The monel metal with which this water comes in contact is the source of nickel and copper contamination, which if allowed to remain in an operating battery would cause the evolution of dangerous concentrations of hydrogen gas. Ion exchange removal of copper and nickel contamination from battery water has been in successful use for almost five years on Naval submarines. The exchange material used in this process is *Duolite C-3*.

Duolite C-3 is a phenolic cation exchange resin supplied in 2½ gallon paraffin-lined fir kegs, and has been added to the Navy Standard Stock Catalog. Other exchanger resins will be made available through the same system after having been tested and approved by the Bureau of Ships.

Installations on all submarines were authorized by the Bureau in 1944. Detailed instructions have been published in a BuShips Bulletin of Information. All submarine overhaul activities and submarine tenders have set up facilities for regenerating and servicing these units. The exchanger unit is a cylindrical tank of hard rubber construction having a volume of about 2½ gallons. The resin bed is supported by a very fine screen made of hard rubber. The resin is loosely packed in the tank to within 3" of the top. The unit is bulkhead mounted in a vertical position between the storage tanks and the battery filling line. One unit is provided for each battery filling connection, and the piping is so arranged that the exchanger remains full of water at all times even when the system is drained.

Each unit is capable of treating about 5000 gallons of contaminated battery water containing 2 ppm of copper and 3 ppm of nickel at a rate of 250 gallons an hour. Moderate air pressure may be used to facilitate the flow. After installation of a new resin bed, 300 gallons of water are run to waste until a sample shows absence of suspended solids.

The resin operates in the hydrogen cycle since sulfuric acid is used in the regeneration of the bed. The removal of nickel and copper is shown in the following reactions:

$$NiSO_4 + H_2X = NiX + H_2SO_4$$
$$CuSO_4 + H_2X = CuX + H_2SO_4$$

The released sulfuric acid tends to make the effluent water acidic, but this acidity is compatible with storage battery electrolyte.

Tests were conducted by the Naval Research Laboratory to determine the effect of the resin upon the battery electrolyte in the event of accidental contamination. Results of this investigation revealed no harmful effect

However, if the exhausted bed material were to be forced into the battery electrolyte, adsorbed copper and nickel ions would be dissolved and would result in the immediate generation of hydrogen gas. It was considered important that backwash rates be limited so as to avoid carrying over of the exchange bed into the battery cells.

Ion Exchange Purification of Boiler Feedwater—The removal of trace quantities of dissolved solids unavoidably retained by water produced by ships' evaporators, was considered some years back by the Bureau of Ships. An intensive investigation at the Naval Engineering Experiment Station was conducted for the purpose of estimating the requirements for a typical shipboard installation. Exchange capacity, amount of regenerant required, and amount of backwash water required were determined by means of laboratory experiments. Computations based upon these tests yielded the following interesting data for a typical destroyer:

Basis for computation—(for two engine rooms)

Total feedwater required for ½ speed—440,000 pounds per hour
Feedwater contamination—20 ppm chlorides
Size of exchange unit—sufficient for 30 hour operation
Storage space for regeneration chemicals for 30 days supply

Results of computation—(for each engine room)

One cation exchanger 40″ by 42″
One anion exchanger 36″ by 36″
Two 150-gallon mixing tanks
250-gallons concentrated hydrochloric acid
1000-pounds caustic soda

It was found that during regeneration it was necessary to by-pass the feedwater during the two hours required for regeneration. Thus only 15/16 of the feedwater was demineralized. The provision of standby units was considered prohibitive because of the critical space and weight requirements. The conclusions of the investigation showed that the method required excessive space and weight for equipment and attendant piping, and necessitated the storing and handling of large quantities of dangerous chemicals. The fresh water required for backwashing and rinsing represented a boiler feedwater loss greater than the losses incurred in boiler blowdown using present equipment to reduce solids to the same limits. Because of the necessity of bypassing during regeneration, it was determined that the method would reduce only 94% of the feedwater to zero chlorides. The method was deemed economically unfavorable, and the test was abandoned.

Partial Softening of Evaporator Feed—Current investigative action is being taken, under a current research contract to determine the ability of ion exchangers to partially soften sea water to a sufficient degree to prevent the formation of scale in shipboard distilling plants. It should be noted that the application does not necessitate demineralization or even complete softening. Demineralized water is more practicably and more economically produced by ship's evaporators. Use of evaporator brine as regenerant provides a self-contained system, eliminating the need for storing and handling regenerating chemicals. While the method has not been given shipboard trial, preliminary laboratory scale tests indicate that the method offers promise.

Oxygen Removal from Feedwater—Experimental work on a complex cuprous salt—amine resin exchanger for removal of dissolved oxygen from boiler feedwater revealed that the capacity expected was in the order of 1 to 5 grains of oxygen per liter of wet adsorbent. The principle of adsorption was based upon the rapid oxidation of the cuprous ion to the cupric ion by the action of oxygen. Regeneration of the exchange bed was accomplished by

using sodium hydrosulfite. While the performance of the exchanger was considered satisfactory, the method was found to be too costly for shipboard use. Moreover, it was believed that the resin used in the tests was totally unstable at temperature of 250° F, the average temperature of boiler feedwater from a deaerating heater. The project was accordingly abandoned.

Desalting kits for producing drinking water—Desalination of sea water was accomplished during the last War through the use of silver zeolites in providing abandon ship personnel and stranded aviators with just enough drinking water to sustain life. The chemicals employed were extremely costly and relatively bulky for the amount of water produced, but these factors were more than compensated for by the wholesale saving of lives.

Not all the salts are removed from the sea water by this process. Some 5,000 part per million of total solids remain after treatment, but this is not of sufficient concentration to cause a physiological effect on the drinker. The kit developed by the Navy is about the size of a camera (5" x 4" x 2") and is self contained in a rectangular tin can coated with a corrosion resistant lacquer. The total weight of the device is about 1½ pounds and consists of a desalting bag of translucent vinyl resin containing an integral filter, and six briquets of approximately 78 grams each, each good for a pint of desalted water. A looped cord is attached to the can and the bag so that the seaman can hang them from his neck and thus prevent loss. Ocean water is scooped into the bag to a marked line (420 ml), the briquet is then dropped into the bag, and the bag then folded at the top and fastened to make water-tight. The briquet is then crushed and permitted to go into suspension. Gentle manipulation and shaking to and fro disperses the suspension, and the water is ready to drink after 15-20 minutes. The water is sucked from the bag through a plastic nozzle fastened to the bottom of the bag. The filter removes the chemicals and the suspended residues, and the water is quite clear and potable. A Navy Aeronautical Specification (7) was prepared for the device, under the title "Drinking Water Kit, Desalting, Chemical".

Potential Uses of Ion Exchangers

Incalculable applications for ion exchangers are possible and it is impossible to predict what these will be in the future. New type resins are appearing each month, especially tailor-made for special problems and uses. Before an ion exchanger material is selected for a particular purpose, an economic study should be made to determine if the candidate material is needed for the job, and if economics support the choice. No set rule can be established for selecting the material, except for the general advice that no ion exchange material should be selected until an investigation of the particular problem indicates that it is the most desirable. Many installations have been made on the false assumption that the ion exchangers will cure all evils regardless of the character. All manufacturers of ion exchange materials will cooperate in providing specifications describing the limits for their materials, as regards chemical stability, capacity, costs, and temperature ranges.

For an industry in its early youth, the ion exchange industry has taken great strides in establishing its place in the chemical field. Great potentialities are in store for this new tool. We may yet see the day when highly concentrated resins in pill form will provide all the ion exchange power necessary to convert a gallon of sea water into drinking water. But this possibility is still "a long way off". It should be recalled that present day exchangers require as much as 3½ pounds of regenerating chemicals for every pound of hardness adsorbed, which makes ion exchange an expensive process for very hard water

There is, however, a great future potential for ion exchange, which is best exemplified in the following quotation taken from a manufacturer's own literature (8):

"It would be folly to suggest that we have reached perfection in ion exchange resins, for each new adsorbent will make possible process innovations that will undoubtedly place additional demands on the capacity, exchange rate, and elution efficiency of the exchangers. The history of synthetic ion exchange resins is hardly a closed book; its binding is barely cracked".

References.

1. Kunin, R., Anal. Chem., Vol. 21, 87 (1949)
2. Way, J., Journal Royal Agricultural Soc., 11, 313 (1850)
3. Smit, P., U. S. Patent 2,191,063
4. Adams, B. A., and Holmes, E. L., J. Soc. Chem. Ind., 54, 1-67 (1935)
5. Adams, B. A., and Holmes, E. L., U. S. Patent 2,104,501
6. Kettele, B. H., and Boyd, G. E., J. Am. Chem. Soc., 69, 2800 (1947)
7. Navy Aero. Spec. M-613, dated 15 August 1944
8. "The Resinous Reporter", July 1948, Vol. IX, No. 4, p. 4.

28-Ft. Plastic Personnel Boat Hull Made by Matching Mold Process, 20 May 1949.
(Small portion of inverted male mold with recesses for framing may be seen in pit at lower right hand corner).

THE U. S. NAVY PLASTIC BOAT PROGRAM

COMMANDER A. C. BUSHEY, JR., U. S. N. R.

A CONTINUATION OF THE PROGRAM AS PRESENTED BY COMMANDER BUSHEY IN THE FEBRUARY, 1949 ISSUE OF THE JOURNAL.

COMMANDER BUSHEY whose previous article on this same subject was published in the JOURNAL of February 1949 is on duty in the Bureau of Ships. A discussion of the earlier article by Mr. J. S. McGuire, President of the Fairfax Engineering Company, Inc., was printed in the May 1949 issue.

Numerous articles on the U. S. Navy Plastic Boat Program appearing in periodicals and newspapers at home and abroad, the sound motion picture of the manufacture of the first 28-ft. plastic boat, the service this boat has rendered to the forces afloat, the exhibition of a completely outfitted 28-ft. plastic personnel boat in the New York and Philadelphia Motor Boat Shows, the outfitting of 28-ft. and 36-ft. plastic craft in one of our Naval Shipyards and the inception of a program in another Naval Shipyard to build 12-ft. plastic wherries have stimulated a considerable amount of continuing interest. The building of 8-ft. to 15-ft. rowboats, sailing dinghies and outboard runabouts of laminated plastic on a commercial basis, the material tests and actual construction carried out by other agencies of government in fibrous glass reinforced low pressure laminates have engendered a more diversified interest. An attempt is made herein to answer some of the questions raised and further, to furnish a brief summary of progress.

Resins used in the manufacture of most plastic craft if used to make castings without reinforcing materials have physical properties generally as shown in the second column below. By referring to the third column comparison can be made with the physical characteristics of the laminated plastic skins of the 28-ft. Navy plastic boats.

	Polyester Castings	*Hulls of 28-ft. Plastic Boat*
Flexural Strength, PSI	11,950	31,000 to 37,300
Tensile Strength, PSI	9,060	27,000
Modulus of Elasticity, PSI x 10^5	5	17.6 to 18.6
Compressive Strength, PSI	10,900	21,600 Edgewise—44,300 flatwise
Izod Impact Strength	0.35	26
Specific Gravity	1.2	1.5 to 1.64
% Water Absorption	0.1	0.17
Rockwell Hardness, M Scale	99	109

These data are presented because repeated suggestions have been made to mix finely divided and macerated fillers in polyester resins and pour into molds and thereby make boats and castings of purportedly great strength. This method and slush molding have both been used to produce non-structural objects for industrial, decorative, electrical and utility purposes. High grade castings of beauty and high impact resistance are being mass-produced at low cost on cheap flexible and rigid molds. Polymerization (the timing thereof is controllable) usually occurs in from 8 to 20 minutes when resins which cure at room temperature without the application of heat and pressure are used. Fillers commonly used are cotton flock, milled glass fiber and asbestos, care being exercised to prevent a weak finished product because of too much finely powdered filler in the blend. It should be emphasized that only long, fibrous reinforced resinous materials, i.e., cotton cloth, paper, glass cloth and mat, sisal, rayon, etc., laminated with proper resins, possess the necessary strength and the general utility to meet structural requirements.

The foregoing appears to indicate and laboratory tests have actually shown that the equality of the best structural laminated plastic depends directly upon the amount of fibrous glass used and the bond between resin and glass. To increase strength, more glass is added. And the best glass mat and cloth for structural purposes are those with the smallest diameter of glass fiber. A good bond, with present materials, is dependent in large measure on the manufacturing technique employed. Better bonding of laminates in boats has been achieved recently by increasing the amount of resin from 52% (amount of resin in first plastic boat, by weight) to 60%. This means a 20 per cent increase in weight of hull for equal strength, but because of assurance of uniform bonding and strength a lower factor of safety could be and was used, resulting in less thickness of hull and thereby maintaining approximately the same weight. This increase in resin content also appears to guarantee complete watertightness of hull.

In fitting out the plastic boats it was necessary to use high speed metal-working machine tools. Care was exercised to cool cutting edges and carry

Speed Trials of First U. S. Navy Plastic Boat in Delaware River, 2 June 1948. (Canopy is of plastic construction similar to that of monolithic hull and decking).

away the dust. Compressed air or water can be used for the former and a vacuum cleaner for the latter

Improvement in the method of making the first plastic boat (described at length in the previous article) was accomplished by the use of aluminum in lieu of wood for framing and through the use of a vacuum blanket instead of the pressure bag or bladder. The aluminum and wood framing assemblies were both non-rigid, the aluminum members being entirely of perforated flat plate, joined by clips to form appropriate sections; all connections being riveted through slotted holes. In a boat recently made by this process, the skin thickness was reduced to ¼", although the resin content was increased from the 52 per cent for the first boat to 60 per cent. The facility with which work was accomplished and the absence of bulky equipment in the manufacture of this 28-ft. aluminum framed plastic boat was reflected in a material saving in time of production.

The five 36-ft. plastic craft contracted for (mentioned in the previous article) have also been built. It is of interest, in this case, to note that the contractor competed successfully against wood as the construction material. Cheap, "one-shot" inverted male molds were used without cover molds, pressure bags or vacuum blankets. Instead of having the service life of only one year called for, tests to date indicate that they compare favorably in nearly every respect with the plastic boats built by conventional methods. It was found that the inhibiting action of air on curing of resins was not a limitation, but an asset for long term progressive lay-ups in that the "kick-over" from a liquid, impregnating resin to a cured, solid plastic could be delayed to facilitate bonding of progressive sections and also to suit production conditions. Further advances were made by the use of room temperature curing resins in the manufacture of three of these boats and by making one of the three with self-quenching (self-extinguishing) resins.

The greatest advance made was with "the fabrication of the 28 Ft. Plastic Boats under the second contract". The procedure outlined in the

previous article was followed except that the thickness of the female plastic mold was reduced from 1½ - 1¾ inches to ¼ inch, heat for curing was eliminated and the resin was drawn up through the laminates by vacuum (in 15 minutes) instead of forcing it under pressure. Uni-directional fiber glass was used in the framing of the boat. This process guarantees a thorough wetting and impregnating of the glass fibers and the vacuum ensures removal of all air, thereby producing a strong, nonporous laminate. The hull, in this instance, was only 3/16 inch thick.

In the matching mold procedure, the wisdom of having a resin "tailor-made" was demonstrated. The exotherm from this room temperature curing resin was only of such intensity as to make the outside of the female plastic mold mildly warm. The resin manufacturer in this instance has made a specialty of making a resin to suit the manufacturing process.

The use of uni-directional fiber glass for the first time presages further application. For high tensile loading the oriented fibers are layed-up in the direction of the stress. Physical tests of boat frames comprised principally of this high strength material have not been made. However, from experimental work, it is assured that the physical properties of such plastic boat frames will be considerably better than those for the plastic boat skins.

Inclusion of light weight materials between the laminates to provide greater buoyancy is now an accomplished fact. A simple method of repairing damaged plastic boats has been developed. One of the resin manufacturers has devised a special kit for this purpose.

Indications are that for mass production of boats up to possibly 70 feet in length, the matching mold process offers much promise. The inverted male mold would probably be built of concrete, surfaced with a resin, recently developed, which would be applied with a paint brush or sprayed to form a hard, glossy and durable molding surface. The female mold would be of laminated plastic, not more than ¼ inch thick, sprayed with the same special resin. This process has the distinct advantage that all materials are handled in the dry state. Uni-directional fiber glass would be employed for framing and mats and cloth in the lay-up of the hull skin. Room temperature "tailor-made" curing resin would be drawn through the laminates by vacuum (5-10 lbs.). This operation would not take longer than one-half hour. This is a simple process which has the added appeal of cleanliness.

It is now believed feasible by utilizing these sundry improvements in manufacturing techniques, with variations and combinations thereof, and, in particular, "tailor-made" resins permitting long term progressive lay-ups, to produce large structures which will justify their manufacture even on a single unit basis. By competing pricewise with other structural materials, laminated plastics will more quickly find their niche in the gamut of acceptable materials.

THE METHOD OF RESEARCH

The Analysis, Organization, and Determination of Resources Required for Undertaking a Research Problem are Discussed and Defined

DAVID B. HERTZ

THE AUTHOR

DAVID B. HERTZ received the degree of B.A. from Columbia College in 1939, B.S. in Industrial Engineering in 1940, and Ph.D. from the School of Engineering, Columbia University, in 1949. Was a Production Engineer for Radio Corporation of America in 1940-1941, left to go on active duty in Naval Reserve. Served actively afloat and ashore until October 1945, leaving as a Lieutenant Commander. Attended Naval Design Course at Navy Postgraduate School. Is presently Training Officer of Volunteer Naval Research Unit 3-1. Was Assistant Director of Engineering Research for Celanese Corporation of America from 1945 to November 1, 1949. Is now Assistant Professor of Industrial Engineering at Columbia University and also engaged in private consulting practice. Is preparing a book "The Theory and Practice of Industrial Research" which will include the material contained in this article.

The importance of research for the advancement of naval engineering is well recognized today and has been emphasized at length in numerous ways. Indeed the Office of Naval Research has done, and is doing, a remarkable job in helping to maintain the flow of scientific information which is essential to vigorous engineering progress. On the other hand, an understanding of the methods which make research "tick" is perhaps not so widespread among engineers. This understanding is essential, both for the administrators of research, and for those who will use the results of the process. The present article attempts to analyze the methods of solving problems used in collective research groups.

Science is *not* research, although research must be used to advance science, and contrary to popular opinion, the "scientific method," while a part of research, it not necessarily synonymous with it. Science has been

defined as ordered knowledge of natural phenomena and of the relations between them, and Roucek has pointed out that, "All peoples, even the most primitive, have a considerable accumulation of knowledge, which is essentially scientific, and make practical application of at least some parts of this knowledge." Thus, science as a body of knowledge is passive—has no life of its own, and of itself cannot add to the accumulation. Action must be undertaken to acquire further knowledge. One form of such action is research.

Research may be defined as the application of human intelligence in a systematic manner to a problem whose solution is not immediately known. Such action *may* lead to an increase in the body of organized knowledge, but this is not a necessary adjunct to the definition. Science is not necessarily dependent on research, but practically considered, the largest part of knowledge accretions have been obtained through activity falling within this category.

An anaylsis of the research process indicates that it comprises, in combination, the following elements: creative mentalities, properly defined problems, systematic problem-solving procedures, and certain types of solutions. All of these elements are necessary, and they are sufficient, and, therefore, the most efficient relative utilization of each will make for the most desirable research procedure in any given application. It is the purpose of this paper to discuss possible principles to be used in comprehending the present practice and the future of research.

It should be noted at the start that these principles, intuitively and deductively inferred from an investigation of the characteristics of the elements of research, are to be considered tentative—the implication is not that they are necessarily invariant in research, but that the elements from which they stem are the same within any reference frame. Even the fixed components are subject to modification in range and intensity. For example, the limits of creative ability in problem-solving can by no means be definitely defined, and evolution and mutation of the physiological elements involved could change them greatly. The intelligence of an Einstein, say, may or may not be within the ultimate order of magnitude which we should look forward to. Also, even those systematic methods which are known and useful are not fixed or immutable; problems and their satisfactory solutions are determined by changing environments. Therefore, these principles are intended to present a tentative rationale which, if applied and utilized to provide a means of measurement of problem-solving efficiency, will be useful and will, at the same time, serve as a basis for a sharper formulation of the theory of the research process.

Principles for guiding research will be determined to some extent by our answer to the question: Given a research problem, of what does a solution consist? To guide the process of research efficiently, we must decide what characteristics an answer must have. If, for example, we were to define a solution to a given problem as that resolution of the environmental situation in which the individual or group acts as though it had achieved a "truthful" answer, we have not bounded the process sufficiently to judge the efficiency of the procedure. If a completely "incorrect" solution serves as the basis for action, it would seem desirable that we should be able to say that the process used had a very low, if not a "zero," measure of

efficiency. Conversely, it appears desirable—and reasonable—to say that the more nearly "correct" the solution obtained is, the more efficient is the research process utilized.

"Correctness" may be determined by the utility of the answer, and not by its ultimate truth-value. Thus, many hypotheses, while they were far from being "correct" in the light of present knowledge, were used to resolve problems in vacuum tube circuits in the early development of the radio and electronic industry. Insofar as research is concerned, it is the correctness of the solution in terms of satisfactorily overcoming the immediate gap in the environmental reference frame, which defines the efficiency of the process. The evaluation of efficiency from the broader aspect of science as a whole, or society as a whole, is quite another matter, and one which will not be considered here.

We shall, therefore, consider that a solution to a research problem has been obtained when the individual or group is able to overcome the gap or obstacle in the particular situation. More precisely, the efficient solution comprehends that measure of reproducibility which completely resolves all of the elements in the given problem. An incorrect solution would have a measure of reproducibility of "zero" (this is a probability measure and does not imply complete non-reproducibility), and the correct solution would have total reproducibility *insofar as the visualized elements of the particular problematic situation are concerned. The research process should be so organized as to give solutions of the required order of magnitude of reproducibility.* Thus, as among research groups, that one will be most efficient, from our point of view, which resolves most of the elements of a particular problem.

Reproducibility here implies that solutions may be more or less complete; it is a scalar factor, and its magnitude depends upon the correctness of its prediction of results which will occur if action is taken based on the solution. For example, a particular research group studying the physics of the solid state and devoting its attention to the solution of the problem of the causes of fracture in metals, might determine an answer in terms of impurities in the crystalline structure. This answer is reproducible if, when the impurities indicated are eliminated, fracture of the type under study no longer occurs. If the same type of fracture does occur, but only under higher loadings, then all the elements of the problem have not been resolved; but if these higher loadings do not enter into the problematic situation as it is conceived by the research group—if it is not necessary that fracture under higher loadings be eliminated—then the solution has a reproducibility of the required order of magnitude.

The lack of reproducibility does not necessarily mean that the solution proposed has no value. If the elimination of impurities in the crystalline structure has no effect on the observable variables involved in the fracture, the solution has no measure of reproducibility with respect to this problem. We should realize, however, that it may well be valuable from the standpoint of broad theory, since it might be a step in the long range development of a particular body of knowledge. Negative or limiting answers may also have implications of reproducibility; in this same case, if the hypothesis were that there is no apparent method of increasing resistance to fracture, action can be taken based upon this solution.

The value of a solution to a research problem may make itself apparent in various ways. The resolution of a particular problematic situation will, in turn, create new problems. The answer which is satisfactory in a given instance may be the focusing of the individual or group attention upon an element or elements of finer detail which were not discernible in the original problem. Such an answer also has implications of reproducibility in that it serves as a basis on which further action is predicted. As John Dewey says, all scientific operations "are such as disclose relationships . . . which become the means of control of occurrence of experienced things . . . " The fact that research which was thought crucial may turn out to be an intermediate step in the solution of the problem serves to emphasize the relatedness of scientific investigations. In whatever terms the answers to a problem are formulated by the research process, the value or utility of these answers in predicting the results of action undertaken as their consequence is indicative of the efficiency of the process itself. And this is the only indication.

The utility of a particular solution to a problem, obtained through research, in enabling an individual or group to take satisfactory action based upon the future results predicted, is the measure of the overall efficiency of the process. Measures of this efficiency are no doubt difficult to obtain. Nevertheless it is apparent that two possible types of solutions should be readily recognizable: gross errors, and solutions with high degrees of reproducibility. If such a system of evaluating the efficiency of a research organization were practiced, refinements could be developed, based on experience and observation, which would better indicate operational characteristics and the relative difficulty of problems than the qualitative methods for such evaluation now in use. Quantitative means are now in use in some industrial organizations, for example, to measure the results of research, but these are generally based upon some type of profit-and-loss calculations which are at least once-removed—and perhaps more so—from the research process itself. The measurements we have defind are in some degree related to these latter, but they are in no-wise the same. Direct application of these concepts to industrial research will not be considered here.

The other elements of the research process must be considered from the standpoint of the solutions reached. Any principles inherent in the utilization of each of the components must be directed toward the production of reproducible solutions. As previously noted elsewhere, the research process begins with a problem of a particular type—either the data or the solution are not simultaneously known, or, if known, they are not desirable. Also, systematic methods of solution commence with the problem—its analysis and definition. From the standpoint of ultimate results, this problem analysis is quite possibly the most important element in the entire process.

The first step in the analysis of any problem presented to an individual or group for solution by the research process is a determination as to whether or not the problem is one suitable for the organization. For example, if it is a routine problem for which both the data and method are available and adequate to give the solution with an acceptable risk of error, it would be inefficient for an organization established for research purposes to expend its resources in attaining a solution. A research organization

exists for the purpose of using creative abilities to solve research problems, and the decision as to whether the problem is suitable or not is often relatively easy to make. The principle should thus be observed that ***a research organization should only undertake the solution of research problems.*** The simplicity and obviousness of this concept are deceptive: in industrial organizations, particularly, much work is done in the name of research which involves none of its elements.

Having made certain that a problem requires the resources of the research process for its resolution, the next analytical consideration is the type of relationships required in its solution. Is the problem one in which the correlation of simple variables will be sufficient, or are elements of organized or disorganized complexity involved? The decision reached at this point will be all-important in outlining the procedure to be followed in the collection of data and achieving the required relationships. Systems of measurement necessary to obtain data for problems involving simple variables may be—and often are—quite complex, but the methods of manipulation of these data in order to make consequential inferences are straightforward and relatively simple. On the other hand, in problems of disorganized complexity the (assumed) random nature of the data adds to the difficulty of their collection. Manipulation of the data, depending as it does upon statistical concepts still in the process of evolution, may also be considerably more difficult. And, further, problems of organized complexity interpose even greater barriers between the investigators and suitable means of arriving at conclusions as well as collecting data. Examples of problems of organized complexity are economic research, market analysis, and opinion determination. The data here are not those of random ordered sets, nor are the manipulatory techniques those of simple statistics.

There is, of course, no different art in the adjustment of an organization to the various types of research problems than in setting up the organization to solve problems efficiently in the first place. The principles are the same. The only change is the situation to which they must be applied. Nonetheless, *the application of the research organization to various types of problems requires a suitable diagnosis of the situation in advance.* Clearly, the organization which undertakes the solution of a problem of organized complexity as though it were one of simple variables is proceeding most inefficiently. Personnel, techniques, and other resources required are apt to be quite different, and unless these are provided in advance, efficient operations will not be possible.

In general, this same analysis should be indicative of the various elements of the problem. Most research problems, and particularly those of industry, comprehend more than one specialized branch of science. This is true for problems of simple variables as well as for others. As Norbert Wiener so pointedly says, "If the difficulty of a physiological problem is mathematical in essence, ten physiologists ignorant of mathematics will get precisely as far as one physiologist ignorant of mathematics, and no further." Therefore, the various elements of which the problem consists must be distinguished and provision made for their investigation.

From our standpoint in this study, this means that a research problem can and should be defined in terms of various sub-ordered problems which may or may not fall within several specialized branches of science. In the

analysis of any problem it is extremely important that the structural elements be distinguished. These elements may be quite diverse, but the thought-directing vectors derived from their recognition are essential to the creative solution. Each of the structural elements may constitute a sub-problem, and insofar as the usual research organization is concerned, it is unlikely that any one individual specialist will have the necessary background, knowledge and creative ability to solve all of them.

This distinguishing between the structural elements of the problem is the definitive requirement of problem analysis, and it must be undertaken even though the problem itself be somewhat vague or hazy. This is simply to say that the process of solution must start somewhere, and it will be most efficient to begin the process with those resources which will ultimately be involved before the solution is reached, if possible. The implication is not intended here that these elements can always be solved as independent entities, although this is sometimes possible; what is intended, is that the problem shall be analyzed and brought into some sort of pattern of its elemental parts.

It is unlikely that each of the elements can be solved independently; it is more likely that each of the parts must be resolved cooperatively and coordinately, with the specialists operating as a team. The composition of this team should depend upon the *a priori* analysis of the problem. It will be necessary that the members of the team communicate with each other, each seeing his own work in relation to the whole, and each understanding enough of surrounding fields to suggest experiments to those who have the specialized skill to carry them out. The professionalized (or, in organizational terms, functionalized by skills) approach, which is used by most research organizations, is not the most efficient method of solving problems involving a complexity of elements, and the greatest number of industrial problems are of this type. *There is a particular composite of creative mentalities which will be most efficient in a given instance.*

The application of this principle in a given organization, while dependent upon the analysis, will also be controlled by the range of resources available. Its use will require, in addition, the treatment of the individuals who form the organization as independent entities, to be utilized as the analysis of a given problem dictates, and not necessarily as occupying a particular location in a formal and rigid structure. That this is not a standard or usual *modus operandi,* and that it requires a novel conception of organizational structure and practice is recognized, but its utility and necessity are becoming more and more evident. Its necessity proceeds from the premise which we make here, that *from a definition of a research problem in terms of a set of problems, the scientific resources and environment optimally suited to its solution may be formulated to a greater or lesser degree.*

The ability of an individual to analyze an environmental situation correctly depends in large measure upon a predetermined attitude or "set." Experimental psychologists have termed this mental condition "einstellung," and have established its existence as a part of the proecss of thinking. In a sense, the historical position of the research worker with respect to the given problem will have a definite bearing upon his resolution of it into elemental components. The broader the scope of his background and knowledge, and the wider his acquaintance with scientific fields outside his

own specialty, the more useful will be the attitude he brings to bear upon the analysis of a problem. It is this "set" which largely distinguishes the laboratory researcher from, say, the development engineer. This is intuitively recognized throughout research, as indicated by such common statements as "The theoretician has an entirely different viewpoint attitude as compared with the applied scientist." Each time a problem is reoriented and the structural elements reformulated, the attitude which could most profitably be utilized for further analysis may be somewhat different. Obviously no one individual can be expected to have a multiplicity of such "sets" toward a given problem. A group is more plastic in this respect, since it is quite possible to shift the collective viewpoint or attitude with the requirements of the situation.

We are confronted, then, with these requirements for problem-solving: There is a particular composite of creative mentalities which will be most efficient in a given problem situation; resources and environment for problem-solving may be pre-determined; it is necessary to analyze a problem into its elemental components before proceeding with the choice of the creative mentalities and the resources for its solution; an individual will bring to a problem a definite attitude or "set" which may or may not be the most fruitful for the analysis of the situation. We would like to advance the thesis that *the collective attitude of the research team, selected on the basis of the requirements of the problem, offers, in general, the most efficient group of presuppositions from which to proceed to its solution.*

On what basis is the group attitude conceived? At no stage in the research procedure can the individual mentalities be completely blank, and each individual will come to the group with his own particular "set." How may these different attitudes be subsumed in a collective "set?" If the analysis of the problem is undertaken on an authoritarian basis, by a director or leader, and transmitted without modification to the group, then one of the advantages of group activity is lost, and except for the *quantity* of work involved, the research might as well be considered individual. Under exceptional leaders, such a procedure may be and has proved to be quite efficient, and can lead to satisfactory solutions. If this transmitted viewpoint is contrary to the collective attitude, the conflict inherent in such a situation could possibly negate the anticipated results of the most brilliant analysis.

In some cases the group approach can indeed simulate the Baconian requirement that all previously formulated solutions be cast aside. Such a situation would arise if opposing attitudes or viewpoints within the group were such as to reduce or negate the overall "set." On the other hand, mutual reinforcement of ideas would tend to strengthen a particular approach. The conception that efficiency would be increased by the use of a collative point of view presupposes that the selection of the group members is sufficiently randomized to cover a broad field, and that the personalities projecting individual attitudes are equal in strength. Neither of these assumptions can be completely realized. The spread of education and transmission of information, and the proper selection of research personnel, can do much to assure the existence of the former condition. As for the latter, the influence of personality within a particular group can be utilized

advantageously by proper administration and direction on the part of the leader. This is a most important concept in the organization and administration of research activity.

In general, the analysis of a problem presented to a group of research workers may be developed in one of the following ways:

1. The analysis may be made completely by higher authority and a pre-determined attitude presented to the group.
2. The individuals may work independently, proceeding on the basis of their own presuppositions.
3. Individual ideas may be presented to higher authority, where another "set" will be added (or subtracted) and the synthesis returned as to the attitude to be followed.
4. The group, including such higher authority as may be required, may collectively arrive at a satisfactory analysis of the problem for further work. If proper safeguards are provided in the selection of personnel and the influence of individual personalities, this is the most efficient general principle of operation to be followed at this stage of collective research activity.

The use of this last concept in research presents the same type of organizational and administrative problems discussed in connection with group attitudes above.

This process of analysis and definition is never completed until the problem has been finally disposed of, and, at each stage in unfolding and evaluation, reformulation and re-establishment of the collective attitude will be possible and useful. Each new set of empirical observations, each newly formed postulated hypothesis will modify the problematic environment so as to enable the research group to shift the experimental "spectrum" toward (or possibly away from) the direction of the desired result. *The importance of this analytical and evaluative process as a continuing activity through all of the stages of a given instance should not be overlooked in the establishment of research principles.*

The individual creative ability is an essential element in the overall process we are synthesizing. The selective grouping of such mentalities and the utilization of their individual attitudes to create a more effective group approach have already been discussed with respect to a rational analysis of problems. What of the individuals themselves? What principles should be kept in mind in order that the individuals' abilities be most effectively utilized?

Probably the most important single element in problem-solving is the realization by the researcher that any given problem may differ, from stage to stage in its solution, in method required and in difficulty of applying that method. It, therefore, is of paramount importance to the administrator of research personnel that he plan the work of his team with this in mind. Two precepts should be followed in assigning individuals to work on projects.

In the first place, *it is essential that the abilities of the individuals be such that they are capable of assuming the responsibility of solving the problems delegated to them.* Clearly, if an individual, as part of a team or alone, be given an obstacle which he is not capable of overcoming, he is not being utilized efficiently. If he does reach a solution, it will be in a hap-

hazard manner, like the hen who finds her way out of a three-sided enclosure to reach food on the other side—the probability is higher that she would starve before achieving a solution to her problem. Similarly, the creative mentality will be used inefficiently if its capabilities are far greater than those required to solve the problems presented to it. The latter case is not as serious as the former for a particular research organization—it is wasteful of resources, but at least the desired objective will be reached.

In the second place, *in weighing the ability of an individual it is important to realize that creative mentalities differ, and the types of mentalities required for different problems, or for different stages of the same problem, may differ.* Thus it may be that one individual could make the necessary intuitive postulates on which to design experiments and collect empirical data, but not be capable of deducing the necessary relationships or making the epistemic correlations required for verification. This is again indicative of the desirability of the team approach, since the flexible research team can be designed so as to include the requisite abilities. In a rigid organizational framework, however, it may not always be possible to select those individuals best suited to a given stage of the problem.

C. E. K. Mees discusses this distinction between abilities in his book *The Path of Science* (John Wiley & Sons, 1946). Speaking of the difference between theoretical synthesis, observation and experiment, and invention, he says:

> Psychologically, each involves distinct methods of working and different types of mind. There is even opposition among them; that is, it is unlikely that one man will excel in more than one direction. It is rare, for instance, for a capable inventor to be a theoretical thinker. Some scientists excel in their ability to visualize general syntheses and thus evolve theories. Some excel in their skill in observation or in their ingenuity in designing experiments. Some have a capacity for inventing and can design entirely new ways of accomplishing their ends. . . . Scientists and technologists can advantageously be classified according to the extent to which they possess the three scientific factors and the ability to organize.

He continues in this vein, classifying Descartes, for example, as a theoretician, Galileo as showing ability along all three lines, Newton as experimenter and theoretician, and Edison as "the inventor *par excellence.*" What makes for these differences among creative mentalities, and whether these are the only ones of importance, are questions open to some dispute, but the recognition of the concept remains.

J. B. Conant makes the distinction between the "scientists who excelled in strategy and those who were outstanding as tacticians." In *Understanding Science* (Yale University Press, 1947) he compares Lavoisier and Priestley as follows:

> Lavoisier's lasting contribution was made because he placed his experiments in the framework of an ambitious attempt to explain a great many facts in terms of a grand conceptual scheme. It would not be too misleading to call him a master strategist in science. Priestly on the other hand, probably excelled Lavoisier as an experimenter but he failed to appreciate fully the significance of his results. . . . It is not unfair to say that he was a great tactician, but a poor strategist.

This is not the place for a fuller discussion of such differences, interesting though they may be. The point is that since such differences in potentiality are recognized as existing among the greatest of scientists, they should certainly be taken into account in attempting to solve problems in a systematic manner with average individuals. *It is necessary to iterate that the greatest single factor in increasing the efficiency of utilization of creative ability in an organization is the selection of problems, and stages of problems, compatible with an individual's capabilities.*

The minimum essentials in the solution of a given problem are the assumption of causality and a definition of the problem, but, once we have these, the choice of specific methodological techniques is quite wide. *The selection of the method will depend upon the analysis of the problem, the individual mentalities involved, and the general character of the team or organization.* The efficiency of the process will vary with the suitability of the method. The use of deductive solutions in a problem of market research, or the use of a strictly intuitive approach to a problem in magnetic field theory could be equally futile. On the other hand, the use of an intuitional approach to a problem by a single individual in an organization, in which all other results are obtained by strict deductive logic based on data at hand, might be the single factor making the solutions obtained useful. Methodology is, and must be, flexible; and while it is possible to state approximately the overall objectives for the solution of any problem—to analyze the situation, to collect empirical data to obtain relevant information, to manipulate these data in such a way as to arrive at inferences and conclusions, to obtain the necessary epistemic correlations and evaluate results—the pattern from problem to problem may vary considerably.

The choice of a method should be considered in the same light as the choice of any other resource. Method is not the be-all and end-all in research, nor is it a random factor whose choice would in no way affect the process efficiency. The selection of a method in advance of any analysis and the imposition of this method upon what may be considered fixed entities in the system would be highly inefficient. Similar considerations as those discussed in arriving at a collective attitude toward problems hold in the choice of the manner of their solution. It may be that more than one method appears feasible, and if so it will be efficient to try all that do. Changes in the attitudes assumed toward a problem, whether of a part or of the whole, will occur from time to time as the situation is modified by the action of the researchers. Changes in method believed to be the most efficient in a given instance (stemming from re-analyses of the problem) will perhaps occur less often, but not so infrequently that any method should be considered inflexible from start to finish.

Such changes may deal with the methods of collecting valid data or with the methods used to manipulate them. The resources of personnel and equipment involved in either situation may be quite complex. For example, a shift from strictly classificatory to statistical methods in drawing inferences, or a shift from the collection of data involving one or two variables in a laboratory to the collection of data in a plant scale operation may entail a complete reorientation of an entire research organization. For this reason, an organization is more efficient if it can anticipate the requirements of possible changes in the methods used to solve its problems.

The modes of measurement available to the experimenter or researchist play a leading role in the type of problems he can solve, and his efficiency in solving them. It was not possible for Pascal, for example, to collect the necessary data leading to the solution of the theory of the pump until Torricelli devised the barometer. The selection or availability of devices for the measurement of the data necessary in problem-solving is an important factor in the choice of a method. In any measuring device, whether it be one to measure physical attributes or value judgements, there will be certain inherent characteristics of sensitivity, precision, and range. In addition to these, the researcher must be assured that the units he is measuring are those relevant to the variables in the particular problem. *Thus, in the ideal case the decision as to the variables necessary to solve the particular problem, the range of limits of the variations it will be necessary to measure, the precision or accuracy of measurement desirable (in other words, an advance estimate of the error), and the sensitivity or response characteristics to a given stimulus would all be pre-determined, and the necessary resources embodying the desired characteristics provided.* Such a situation is by no means usual, and very often compromises must be made with one or several of these requirements. A more unhappy case, and one which is quite common in research on problems of organized complexity, is that in which the units chosen to be measured are not even relevant to the problem itself.

To a great degree the experimenter or research group has established the limits of possible results before the solution to the problem has been attempted. While it is not always possible to vary the means or instruments available in a given instance, nevertheless the type and nature of the problems which can be solved can be outlined in advance by the same type of analysis we have advocated previously, this time considering the problem in the light of the instrumental means available to solve. Exploratory work can be of great assistance and is definitely required in making all decisions of this type. Such work has been tacitly assumed in our discussions, as a part of the complete analysis of the problem.

The concept of control is part of the same pattern. Control is not evoked for its own sake—systematic experimentation is purposive. By its use researchers can more efficiently hypothecate relationships and abstract relevant information from observed data. The use of more complex measures of control than are necessary is no less inefficient than the lack of sufficient control preventing the satisfactory prediction of results. Thus, the most refined statistical tests of significance would not have assisted Galileo in reaching more comprehensive conclusions from his experiments upon the motion of an object on an inclined plane. It is better here also to err on the side of excess if a research organization is to attain its objectives. Exactitude is not possible, and *it should be a guiding principle of research to provide sufficient means to perform the measurements necessary to obtain an answer in a specific instance, including the measurement of relevant variables in consistent units with satisfactory range, sensitivity and control to provide the desired aspects of reproducibility.* Laboratory conditions do not necessarily provide these factors; or, as C. W. Churchman says in *Theory of Experimental Inference* (Macmillan, 1948):

> . . . we have gradually been led to abandon the older concept of a laboratory science, and to redefine the meaning of experimental control

in a more general manner. We have been led to this revision on two counts: (1) it is no longer obvious that laboratory techniques are *sufficient* for answering critical questions, even in the physical sciences, and (2) it is no longer obvious that the laboratory is necessary for obtaining a set of reliable data on a given question.

By this he means that the conditions within the laboratory may be such as to be sufficiently at variance with those of the general environmental situation that predictions based on laboratory results will be unsatisfactory. Further, the development of statistical techniques for arriving at inferences as to the effects of a multiplicity of variables makes it possible to answer questions in situations beyond the confines of rigid experimental design. He continues:

> This means that the experimenter must become precise enough as to the meaning of his question so that a set of specific observations can be judged regarding their adequacy, and become general enough in his presuppositions about the natural order so that he can decide whether a continued sequence of observations would approach some limiting value . . . it would be foolish to expect that this demand can actually be satisfied in the early stages of scientific developments. But the process of discovery becomes scientific if and only if such control exists, regardless of whether the investigation takes place inside a laboratory or not.

We have been concerned with the formal aspects of inquiry only insofar as they relate to the actual process of problem-solving. Therefore, we may say that a great many research problems may be resolved which are not "scientific" in the above sense. However, there may be problems in which the predictions resulting from the research solution will be in no sense valid without statistical control. Such problems particularly relate to the fields of the social sciences, and to large-scale conceptual schemes in the physical fields such as quantum mechanics. Where the laboratory results are not sufficiently reproducible to answer a question, resort is made to "pilot plants," "life tests," "sampling techniques," etc. If these give the desired results, well and good. If not, then it is certainly inefficient to employ them. The choice of method should be made on the basis of the analysis of the obstacle in the environmental situation which is to be overcome, and the total resources available to the research organization to achieve this purpose.

Many seemingly factual problems are, when examined more closely, questions of value; value judgements are necessary. As John Dewey has pointed out, a physical standard is not a value, but a physical definition with respect to quantity. Nonetheless, in making many laboratory measurements judgement is required—a judgement of the value of the coincidence or comparison observed. A child can be taught to take a measurement with a yardstick, but he cannot be taught to evaluate the significance of his measurement. Judgements in general have two functions: either they distinguish parts in the whole, or they distinguish a whole among the parts. These can be called the functions of discrimination and unification, or the functions of analysis and synthesis.

The difficulty of establishing valid procedures for the application of value judgements and for the answering of questions of value does not imply that such tests can by any means be eliminated from research procedures. The coordinated combination of judgements of a group selected as best fitted to solve a given problem is probably the best answer that can be given to this question under the present circumstances. The unification of our sciences is one approach. Wiener's *Cybernetics,* combining physiology, mathematical statistics, and electronic theory to form a method capable of dealing with problems of "control and communication in the animal and the machine" is one example of attempted unification, and there are others.

The recognition that judgements enter into the research process, and that judgements are increasingly valid as they are made from an increasingly comprehensive point of view, whether analysis or synthesis is involved, is of considerable—if not paramount—importance to research. Any neglect of this will have a definitely adverse effect upon the efficiency of an organization. Further, as the tendency has been to move scientific problems out of the relatively pure air of the laboratory into the "contaminating" environment of the world, and as this "contamination" has made the study of surrounding fields mandatory if valid conclusions are to be reached, it may be, as Churchman thinks possible, that the unification of science is necessary for the progress of science.

In conclusion, the answer to the question of the most efficient manner of arriving at satisfactory solutions to research problems in a collective organization may be given by the following general principles:

1. An active analysis of the problem or problems in terms of complexity, attributes, compatability with the capabilities of the organization, and structural elements or sub-problems.

2. Determination of the mental, logical, and physical resources necessary for the achievement of a solution.

3. Continuing re-analysis as results are obtained, and re-evaluation of resources required.

4. A unified or cooperative approach utilizing those resources capable of providing a solution.

Further orientation toward the process of inquiry is provided by John Dewey in *The Quest for Certainty;* he describes its general characteristics as follows:

> The first is the obvious one that all experimentation involves *overt* doing, the making of definite changes in the environment or in our relation to it. The second is that experiment is not a random activity but is directed by ideas which have to meet the conditions set by the need of the problem inducing the active inquiry. The third and concluding feature, in which the other two receive their full measure of meaning is that the outcome of the directed activity is the construction of a new empirical situation in which objects are differently related to one another, and such that the consequences of direct operations form the objects that have the property of being known.

These principles will provide a means for concerted endeavor and attack upon all types of research problems. An efficient organization will certainly not be one in which each individual will be doing the same thing. Each individual must be given responsibility for a certain share in the overall task, his duties must be defined, and (as we have noted) his capabilities must be suited to those duties. In addition, he must understand what is required of him. The task of delegating and defining these responsibilities so as to carry out the collective research process in accordance with these principles falls within the province of administration and organization. A knowledge of the background of creative ability and the scientific method is essential as a guide to understanding the progress of scientific knowledge by means of research, although the principles elicited from this study may as yet be impossible of exact application.

LONGITUDINAL VIBRATION

An Energy Method of Estimating Frequency

BY C. S. L. ROBINSON

THE AUTHOR.

MR. ROBINSON was graduated from Harvard University A.B. cum laude and M.S. in mechanical engineering. From 1935 until 1941 he was employed in several apparatus departments of the General Electric Company after taking a year of their engineering advanced course.

Since 1941 he has been with the Shipbuilding Division of Bethlehem Steel Company, working on design problems in marine engineering and doing developmental work in vibrations and fluid dynamics.

This article was published in the August 1949 JOURNAL. *It is here reprinted to correct symbol errors in the original printing. This printing is a substitute for pages 597-598 of the August issue.*

The Rayleigh method is used here to solve for resonant speeds excited by propeller blade frequency thrust impulses. These are important in large geared turbine ships with long shafting.

The use of an energy consideration rather than a system of force equations (as in the Holzer method) is made desirable by the fact that the mass of the shafting is considerable. The fundamental relationship is:

Max Total Kinetic Energy = Max Total Potential Energy.

This method is used to solve for the lowest natural frequency, which is the only one low enough to be considered. An adequate shape for the curve of vibration amplitudes can be calculated by considering the shafting with attached masses as a column loaded in compression or tension. Actual amplitudes are not absolutely determined because excitation and damping are not included.

Nomenclature:

All flexibilities are expressed as equivalent length of line shaft.

A = Cross section area of line shaft.

f = Deflection or assumed amplitude at one point.

f_{av} = Average deflection between two points.

Δf = Relative deflection between two points.

W = Weight of a rigid mass at one point.

$w\Delta x$ = Weight of a length of shafting between two points.

F = Axial force in shafting at one point.

F_{av} = Average axial force in shafting between two points.

ω = Natural frequency in radians per second.

I Deflections:

Refer to Figure 1

The node will be located where the foundation flexibility begins. This may be considered the anchor point, and the weights of the vibrating masses may be considered the loads. All flexibilities including that of the thrust bearing should be converted to equivalent length of line shafting.

A curve of total load (F) vs. equivalent length should be constructed. Concentrated masses will be represented by abrupt increases in F while the distributed mass of the shafting will be represented by a gradual increase.

The loading, (F) divided by AE is the slope of the deflection curve. Hence the deflection curve itself may be found by numerical integration. The anchor is taken as the point of zero deflection.

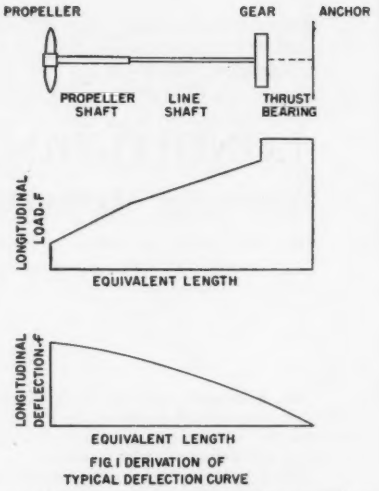


FIG. I DERIVATION OF TYPICAL DEFLECTION CURVE

II Kinetic Energy:

The maximum vibration kinetic energy is

$$\frac{\omega^2}{2g}\left(\Sigma\, Wf^2 + \Sigma\, w\Delta x\, f_{av}^2\right)$$

The summation can be made from a tabulation of the known loads and the deflections calculated above, with ω^2 remaining unknown.

III Potential Energy:

The maximum vibration potential energy is

$$1/2\, \Sigma\, F_{av}\, \Delta\, f$$

It will be apparent that this is determined from a tabulation of the strain energy in each section of (equivalent) shafting.

IV Natural Frequency:

From equating the kinetic energy to the potential energy

$$\omega^2 = g\,\frac{\Sigma\, F_{av}\ \Delta\ f}{(\Sigma\, Wf^2 + \Sigma\, w\Delta x\, f_{av}^2)}$$

This is for the one node or lowest natural frequency. To date higher nodes have frequencies so far beyond any that can be excited by the propeller that their calculation is not necessary.

Conclusion:

The novelty of this method lies in its consideration of the shafting as distributed mass rather than lumping it with the gear and the propeller. This refinement is of value since the shafting weight may be several times that of any other component. This is true with long shafting and it is only with long shafting that primary resonance will be encountered. In torsional vibration problems the small radius of gyration of the shafting makes its rotational inertia negligible. A corresponding analogy does not apply to longitudinal vibration.

Another advantage of this method is that it could include the effect of adjacent masses in the machinery room if they should be coupled to the vibrating system. After their relative amplitudes are estimated or observed, their influence on the resonant frequency may be surmised by including their kinetic and potential energies in the calculations.

REFERENCES.

J. P. DenHartog "Mechanical Vibrations" 3rd Edition McGraw Hill Book Co. 1947.

C. P. Rigby "Longitudinal Vibration of Marine Propeller Shafting"—noted in JOURNAL OF AMERICAN SOCIETY OF NAVAL ENGINEERS, P341, August 1948.

PART TWO

REPRINTED ARTICLES

The articles contained in this Part Two represent those which, in the opinion of the editorial staff, are the most valuable which have been gleaned from recent issues of contemporary publications.

This material was formerly published under the heading "NOTES". It has been given somewhat more prominence and made more readable to enhance its value. The editors' purpose here is to provide a convenient repository to readers of the JOURNAL, for articles originally published elsewhere which contribute to the purpose of the Society: to further the advancement of naval engineering.

Official Photograph National Military Establishment

SKYSTREAK (D-588) in Flight.

SURFACE TREATMENT OF DIESEL ENGINE PARTS.

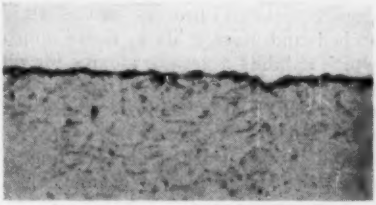
ACKNOWLEDGMENT.

This article, reprinted from "Motorship" for October, 1949, discusses methods for the treatment of metal surfaces to retard the effects of wear.

Perhaps the most critical period of a diesel engine's entire history of operation occurs during the running in time when the engine is new and is being operated in actual installation for the first time. In this respect, the diesel is no different from other types of power machinery, and to a measureable degree, the extent of its future life and quality of performance are dependent on intelligent operation during the critical break-in period.

Slow run-ins with light loads and excessive amounts of lubricants are among some of the measures taken to prevent scuffing and excessive wearing of metal parts operating as bearing surfaces, or in contact under relatively heavy load. The problem has been approached as well through the use of more selectively finished surfaces and precision finished surfaces have reduced the number of failures in some instances.

Surface coating is another technique employed in industry to prevent scuffing, galling, seizing and excessive wear during break-in periods, or where borderline lubrication exists. Such coatings may be achieved by electric plating, which is satisfactory in certain instances, or by effecting a chemical as well as physical change in the surface metal itself.



A photomicrograph at 100× showing a cross section of a Parco Lubrite coating on finished cast iron.

By such a chemical change, steel or cast iron surfaces are rendered more impervious to the effect of scuffing and wear and engine parts so treated have demonstrated an ability to survive the break-in period in better condition than untreated parts.

Surface treatments most representative of the various proprietary processes currently available to engine manufacturers include treatment by caustic sulphur, controlled oxidation of iron surfaces and a manganese iron phosphate treatment that etches the surface of the part and chemically converts it to a non-metallic coating.

The first of these, the caustic sulphur treatment, requires the immersion of parts to be treated in a hot aqueous bath consisting of fifty per cent of sodium hydroxide by weight to which one per cent of powdered sulphur is added. In the chemical reaction between the metal and solution, the compounds sodium sulfite and sodium thiosulfate are formed (the latter more familiar to photographers as "hypo"). During the reaction, steel or iron parts acquire an etched porous surface and a thin top coating of a ferrous sulphide.

Surfaces properly treated by the caustic sulphur process are slightly etched and have a dark, matte finish which exhibits a greater affinity for oil than machined surface. To some degree, tool marks and scratches on machined or ground surfaces are removed in the process, and welding is partially blocked by the chemical film that is formed.

Comparison tests have revealed that untreated cast iron diesel engine cylinder liners show the effect of excessive scuffing caused by welding of metal to the rings under pressure. During a six-hour break-in period, as the ring worked around the piston groove, the entire cylinder liner surface was scuffed wherever it was in contact with the ring. However, liners treated in caustic sulphur solutions, under identical conditions, showed smooth uniform surfaces with no evidence of scuffing or scratching.

On the basis of field reports of several hundred diesel engines in regular service, it is estimated that such surface treatment of vital moving parts had reduced scuffing to about one-tenth of what might be expected of untreated parts during break-in.

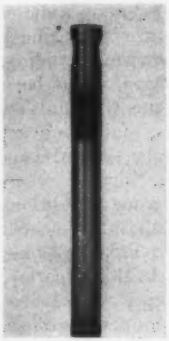
Another process of surface treatment involves the production of the black, magnetic ferrosoferric oxide on the surfaces of cast iron parts. This treatment has been confined to cast or chilled iron parts as the high temperatures necessary to produce the desired oxide would result in the annealing of steel with consequent change in its physical properties.

In the course of this treatment, parts to be processed must be rendered thoroughly dry before placing them in a dry-air furnace where temperature is held at 1100 deg. F. After it is certain that the parts to be treated have reached temperatures safely in excess of 212 deg. F., enough steam is introduced to effectively purge all air from the furnace by the time temperature of the parts reaches 800 deg. F. Parts under treatment then are allowed to reach temperatures of 1100 deg. F., which is held for the time required to form a ferrosoferric oxide coating.

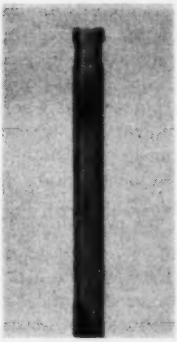
The process must be rigidly controlled and considerable care must be exercised in the initial heating of the parts to prevent the formation of rust, or ferric oxide, which is produced at temperatures under 212 deg. F. in the presence of water. Hence, the importance of thoroughly drying parts before processing and maintaining a dry air condition in the furnace.

This method of surface treatment has been used with good results on chilled iron followers or tappets and cast iron piston rings. Although thus far somewhat limited in application, reports of its success have established it as an integral part of the manufacturing process followed in the production of well-known piston rings.

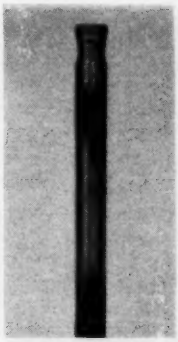
A process developed by the Parker Rust Proof Company of Detroit has been used with considerable success in the treatment of diesel engine parts.



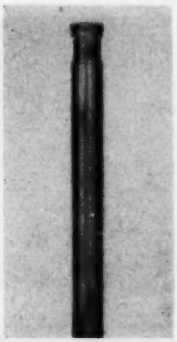
5 micro-in. finish valve stem run in a burnished finish guide without surface treatment.



5 micro-in. finish valve stem run in a rough reamed guide coated in Parco Lubrite.



30-40 micro-in. finish valve stem run in a burnished finish guide without surface treatment.



30-40 micro-in. finish valve stem run in rough reamed guide coated in Parco Lubrite.

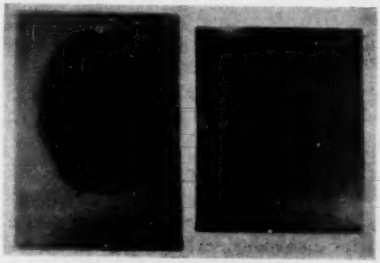
This is a method by which metal surfaces are etched and replaced by a deposit that is non-metallic in its properties, consisting chiefly of iron and manganese phosphates.

This technique briefly described, involves the preparation of a cleaning bath from an aqueous solution of manganese dihydrogen phosphate. This is a primary soluble salt, formed by the action of phosphoric acid on manganese carbonate, and which, when added to water, yields other secondary and tertiary salts and free phosphoric acid.

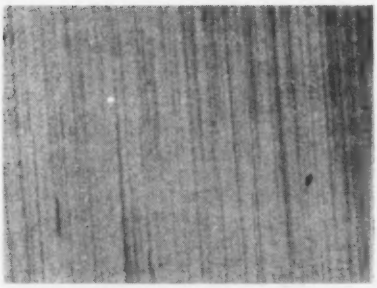
When parts to be treated have been properly prepared they are immersed in this bath. The free phosphoric acid present in the solution reacts with the surface of the metal producing in the reaction, a primary iron phosphate. As more hydrogen is replaced, the reaction continues, producing secondary iron phosphates and resulting in supersaturation of the coating bath which already holds manganese phosphate in solution. As the reaction between the acid and metal approaches completion with the liberation of most of the available hydrogen, secondary and tertiary iron and manganese phosphates precipitate in mixture to form a coating on the metal surfaces in contact with the solution.

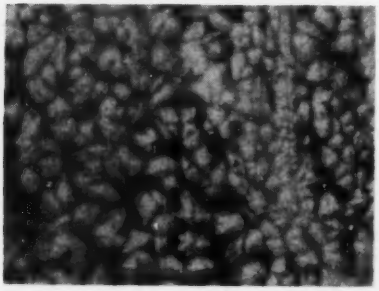
As it is liberated, an added agent in the bath oxidizes the hydrogen to form water, which prevents the accumulation of hydrogen bubbles on the surface of the metal and insures an even etch and uniform deposit of the coating mixture. After certain post-coating processing is completed, the treated parts are ready for installation.

Phosphate coatings on cast iron or steel surfaces possess several important properties that tend to reduce the effects of scuff and wear. The non-metallic coating is an effective barrier against welding which often occurs in metal to metal contact operating under load. Further, the phosphate coatings produced are oil-absorptive, thus promoting better lubricant distribution during the critical period of running-in.



Note the comparative spreading rate at the left, of a drop of oil on a Lubrized steel surface and a similar untreated surface, at the right.





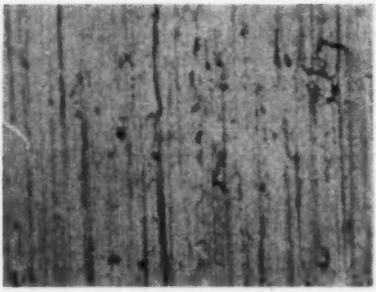
The upper cut shows a microphotograph of a finished steel surface as it appears without treatment. Directly below this is a microphotograph of a similar surface after Parco Lubrizing treatment.

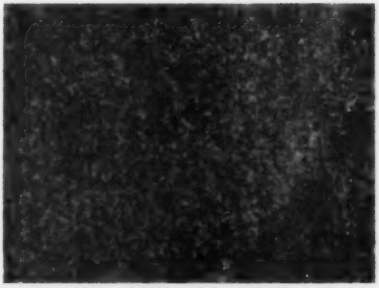
Working surfaces in constant rubbing or intermittent contact are more perfectly lapped-in when they have been treated by the iron-manganese phosphate process. In a situation like this, the chemical coating acts as a mild abrasive, breaking down finally to a fineness that does not further abrade. Because of this ability to increase contact areas, the phosphate treatment has been used with considerable success on gearing.

Even after the phosphate coating has been completely worn away, the underlying etch on the surface of the base metal has considerably greater qualities of oil adsorption than machine finished or plated surfaces.

Among the moving parts on a diesel engine, valve stems are particularly vulnerable to scuffing and welding. Under careful observation, it has been reported that where stems with finishes of varying smoothness failed during run-in in both rough seamed and broached guide holes, similar stems stood up under the same conditions when operating in phosphate-coated guides, showing only a light polishing effect with no pick-up. In this situation, the best practical results were obtained with smooth-bored guides, surface roughness of 20 to 35 micro-inches.

The treatment of small pump parts





The upper cut is a photomicrograph of the untreated surface of a ground cast iron piston. Below it is a photomicrograph of a similar surface after Parco Lubrizing. The diameter increase of .0004 to .0006 in. can be halved by buffing.

with this process has made possible the use of stamped soft steel in its "as rolled" state for covers and spacer plates without further heat treating or hardening. Phosphate coating of steel shafts and cast iron bearing has eliminated the necessity of sleeve bearing in many cases. Coating of the shaft also has increased the life and performance of the usual spring loaded seal running on the shaft.

In such instances as mentioned above and in many others, considerable evidence has been gathered to credit surface treatment with the prevention of failure of many working parts and superior run-in performance. In addition, in the case of iron-manganese phosphate treatment, the use of surface treatment in the manufacture of parts may permit broader tolerance in finish and less critical machining processes, which, in large productions, may represent substantial savings.

It seems definitely established that the proper surface treatment of vital engine parts will contribute significantly to their length and quality of service. Carefully controlled and observed tests have indicated the superior qualities of surface treated over bare metal parts of diesel engines and driven equipment. Such benefits to the user of power equipment eventually accrue to the benefit of the manufacturer and the additional cost of such processing would appear to be a sound investment in superior quality.

MECHANISM OF CREEP IN METALS.

ACKNOWLEDGMENT.

This article, by G. R. WILMS, B. Met. E., and W. A. WOOD, D. Sc. of the Baillieu Laboratory. University of Melbourne, Australia, is reprinted from "The Journal of the Institute of Metals" for April, 1949. It discusses how the mechanism by which a metal deforms at elevated temperatures differs from that operating at normal temperature.

I—INTRODUCTION.

The present paper describes some observations on the mechanism by which a metal deforms when subjected to stress at elevated temperatures. It shows how the mode of deformation differs from that at normal temperature, and how the difference depends on the rate at which the deformation takes place.

A metal under stress as the temperature is raised tends to develop the slow continued deformation which has become known as "creep", and which forms the major problem in the development of alloys for use at high temperatures. The results now described, therefore, are related to this problem, and it is convenient first to refer to the two principal features already established in work on the mechanism of creep. Attention is confined throughout to deformations and to temperatures sufficiently below the melting point for the behavior of the metals not to be complicated by recrystallization.

The first feature, discovered by Andrade,[1] is that creep may be analyzed into two components. One is a deformation which begins at a relatively high rate as the stress is applied, but then dies away; the rate of deformation finally vanishing after a time depending on stress and temperature. The other is a superposed deformation which continues at a constant rate until the stage of fracture. This rate, usually termed the "minimum creep rate", again depends on stress and temperature; it is negligible at normal temperature and very low stresses, but assumes overriding importance as the temperature is raised. These components have been aptly described in a recent paper by Orowan[2] as "transient" and "quasi-viscous" creep, respectively.

The second feature is that the two types of deformation are physically distinct. One proof of this point was obtained by Hanson and Wheeler[3] from an elegant metallographic study of mechanically polished specimens of aluminium stressed at various temperatures. At normal temperature, with the transient component as main factor, deformation of the grains occurred by the familiar process of slip. But at higher temperatures, when the quasi-viscous component was the operative factor, the characteristic slip lines were no longer observed on the surfaces of the grains; instead the grain boundaries became emphasized by an apparent thickening. Hanson and Wheeler, therefore, described this latter creep process by the term "slip-less flow". Whether the slip lines were really absent, or whether they were on too fine a scale to be visible by the microscope, was uncertain; but the difference observed in the mode of deformation was of obvious significance. A second proof of a difference in mechanism was obtained more recently by Wood and Tapsell[4] using X-ray diffraction. Plastic deformation of a polycrystalline metal at normal temperature breaks down the grains to sub-microscopic crystallites of varying orientation. Wood and Tapsell showed that this fine breakdown did not occur in slow deformation of aluminum specimens at sufficiently elevated temperatures, but instead the grains tended to preserve their entity. Whether they did so by a process resembling recrystallization or growth of the crystallites was not clear; it was evident, however, that at the higher temperature the normal mode of plastic deformation was different or profoundly modified.

Consideration of the above-described observations suggested that more definite information would follow from a correlated metallographic and X-ray study on identical specimens, and this approach has been followed in the present investigation, with results which could not have been obtained by either method alone.

Perhaps the main result is the direct observation of a new mechanism of deformation. This appears to consist, briefly, of dissociation of the grains into relatively coarse units, which can be observed and measured, and a process of flow by the bodily movement of these units within the parent grain. The mechanism predominates as the temperature becomes higher and the rate of deformation slower, and is probably that responsible for the quasi-viscous component of creep. It occurs without giving rise to the slip lines which characterize the more familiar deformation at normal temperature, and therefore gives the appearance of the "slip-less flow" noted by Hanson and Wheeler. Since the units are considerably coarser than the sub-microscopic crystallites involved in deformation at normal temperature and rates of testing, they will be distinguished from the latter by the use of the term "cells".

II.—Experimental Work.

After a preliminary description of the material used for the experiments (aluminium) and the relevant techniques, the observations are described most conveniently in the following order:

(1) Specimens deformed at various rates at room temperature. These will provide a standard of comparison.

(2) Specimens deformed at *slow* rates at elevated temperatures. These give the evidence for the cell formation.

(3) Specimens deformed at *faster* rates at elevated temperatures. These show how the cell structure is modified by the speed of deformation and therefore by the presence of the transient component of flow.

Finally, the results are discussed with reference to the two components of creep and to the strength of metals at high temperature.

III.—Material and Preliminary Data.

The material employed was aluminium of 99.98% purity from which flat tensile specimens were obtained of ⅛ in. thickness, ½ in. width, and 1¼ in. length in the parallel test length.

The specimens were annealed to give a grain-size of approximately 0.2 mm. The X-ray back-reflection rings then consisted of sharp, separated reflection spots, a condition which has proved most suitable for observing the subsequent imperfections and breakdown of structure produced in the individual grains by plastic deformation. These stationary back-reflection photographs were obtained with Cu$K\alpha$ radiation, which gave the (511), (333) rings. The transmission and Laue types of photograph, sometimes used for investigations of the present type, have been found much less sensitive and less informative.

When the specimens were in a suitable condition for the X-ray work, they were then polished so that they should be suitable also for metallographic examination under the microscope. The polishing was carried out electrolytically in order to obviate the surface deformation inherent in mechanical polishing. The electrolyte used was a standard perchloric acid-acetic anhydride mixture.

The extension of the specimens was carried out in various ways: by progressive loading with different time intervals between the loads; by allowing continued extension at a given load as in ordinary creep-testing; or, in special cases, by fixing one end of a specimen and attaching the other to a geared-down motor which forcibly extended the specimen at a constant strain rate of approximately 0.01%/hr. For the experiments above room temperature, the specimens were held in a thermostatically controlled furnace.

IV.—Specimens Deformed at Room Temperature.

As already indicated, the X-ray and metallographic changes described in this Section are put forward to provide a standard of comparison. The specimens examined included

(*a*) a specimen extended 10% in approximately 19 min.;

(*b*) a specimen extended 10% in approximately 35 hr.;

(*c*) specimens forcibly extended up to 10% at the constant rate of 0.01%/hr. The first two specimens were extended by tensile loading in increments of 160 lb./in.^{2}, applied in the first case at 30-sec. intervals to a final stress of 6180 lb./in.^{2}, and in the second case at hourly intervals to 5600 lb./in.^{2}

It is necessary to consider one specimen only since the changes were essentially the same for each, being those characteristic of the normal mode of deformation by slip.

The changes shown by the X-rays for specimen (*a*) are illustrated in Figs. 1*x* and 3*x*, the former being taken before deformation and the latter after the 10% stretch. The feature to be noted for purposes of later comparisons is the transition from the sharp, discrete spots reflected from the initial perfect grains to the continuous and slightly diffuse rings typical of the deformed state. The occasional traces of reflection spots in Fig. 3*x* would disappear on further extension as the effects penetrated more uniformly throughout the grains. The interpretation of the X-ray changes has been discussed previously.[5] It will be sufficient here to indicate that the *spread* of the initial spots to continuous arcs signifies a breakdown of the perfect grains into variously oriented elements reflecting over an appreciable angular range; and that the *continuity* of the arcs indicates a breakdown into a number of elements sufficiently large for the individual reflection spots from them to coalesce into an apparently continuous ring. It has been shown that this latter condition involves breakdown to a size less than 10^{-4} cm.; also that there is a limiting lower size to which the elements can be broken down by mechan-

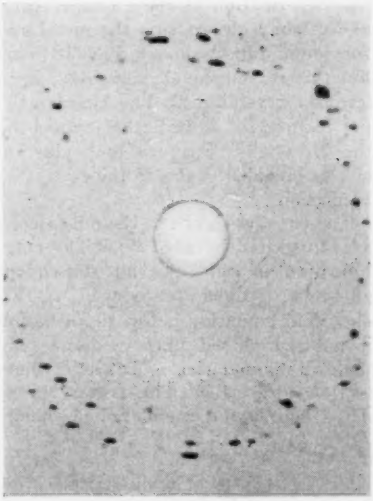


FIG. 1x—Annealed State Before Straining.

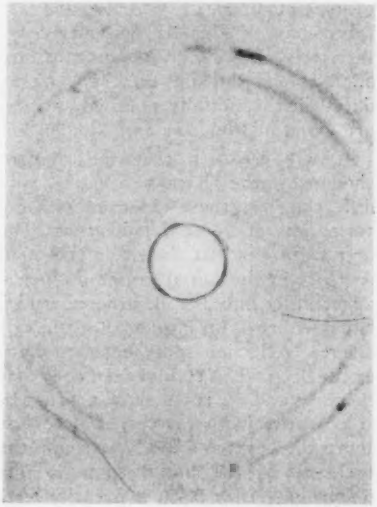


FIG. 3x—X-Ray and Metallographic (x 100) Changes After 10% Extension at Room Temperature.

FIG. 3m—X-Ray and Metallographic (x 100) Changes After 10% Extension at Room Temperature.

ical deformation at room temperature, a size which depends on the metal and for aluminium is about 5×10^{-5} cm. For this reason the elements have been termed "crystallites". The characteristic feature of deformation shown by the X-rays is therefore the reduction of the annealed grains to the crystallite formation.

The changes shown by the microscope are illustrated by Fig. 3*m*. (The magnification of this and all subsequent photomicrographs reproduced is 100 dia.) The condition before deformation is not reproduced since it shows only the grain boundaries, as in a later illustration (Fig. 4*m*). The feature to be noted here is the much studied change whereby the grains become traversed by systems of sharp slip lines, with their appearance of approximate parallelism and regular spacing. As is well known, they represent the dividing lines between parts of the grain which have slipped relatively to each other on deformation. Their relation to the crystallite formation shown by the X-rays is an interesting point, but is not pursued here, as it is desired only to discuss the modifications of each formation when the process of deformation is carried out at higher temperatures. The abovementioned changes together will be regarded as characterizing the mechanism of deformation by slip.

V.—Specimens Deformed *Slowly* at Elevated Temperatures.

The points brought out in this Section are that on slow deformation at a sufficiently elevated temperature the mechanism of deformation by slip is replaced by one in which the grains dissociate into a coarse cell-structure with absence of slip lines; that the process of deformation then involves the relative movement of these cells in the parent grains; and that these units or cells are not the product of recrystallization.

In order to limit the number of photographs for reproduction, the observations in the first place will refer to one typical specimen. This is a specimen at 300° C. allowed to extend under a single load of 530 lb./in.^{2} and examined metallographically and by X-rays after various extensions. For each examination, the specimen was unloaded and cooled to room temperature. The regularity of the deformation-time curve was thereby disturbed, but it was not the object of these experiments to obtain quantitative curves or precise mechanical test data.

The specimen was examined after extensions of 1.2% reached in 2½ hr., 3.3% reached in 8½ hr., and 11.2% reached in 56 hr. The X-ray photographs obtained at these stages are reproduced in Figs. 4*x*, 5*x* and 6*x*, respectively. The corresponding photomicrographs, showing the changes produced in the initially polished surface, are given in Figs. 4*m*, 5*m*, and 6*m*.

It will be seen that the changes shown by the X-rays are radically different from those observed with deformation at room temperature. The first feature is that the sharp reflection spots from the initial grains no longer degenerate into the continuous rings, but now break up into small groups of discrete reflection spots, each as sharp as the original. A second feature is that these secondary spots show a progressive scatter with increasing deformation; thus, after 1.2% extension the break-up of the initial spots is just discernible, after 3.3% it is easily seen, while after 11.2% the scatter has so progressed that the general distribution

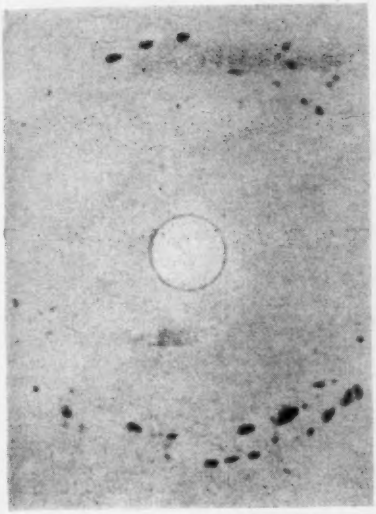


FIG. 4x—X - Ray and Metallographic Changes After Creep at 300°C. (1.2% in 2½ hr., 530 lb./in.²).

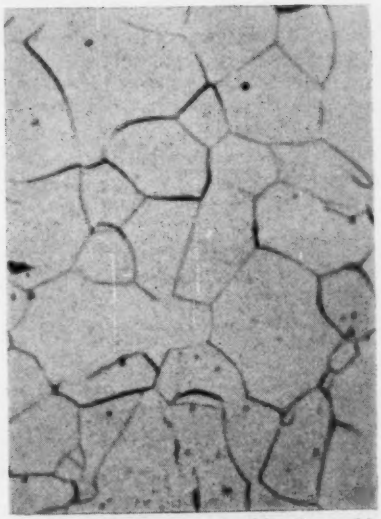


FIG. 4m—X - Ray and Metallographic Changes After Creep at 300°C. (1.2% in 2½ hr., 530 lb./in.²).

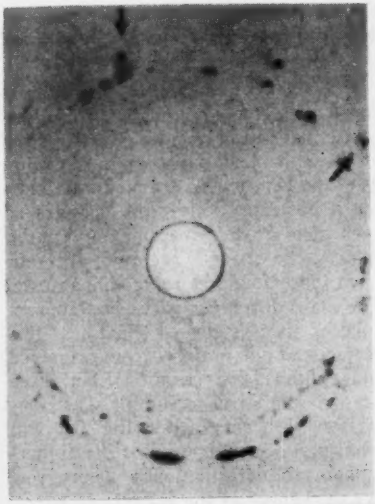


FIG. 5x—After Further Creep at 300°C. (3.3% in 8½ hr., 530 lb./in.²).

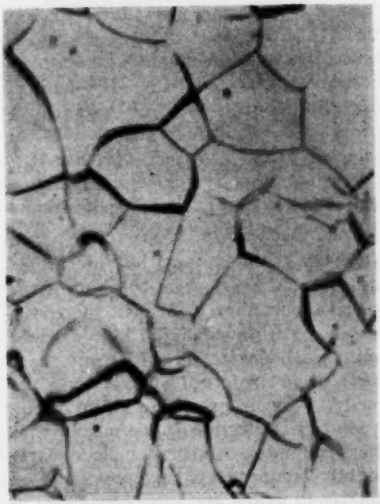


FIG. 5m—After Further Creep at 300°C. (3.3% in 8½ hr., 530 lb./in.²).
(Magnification of photomicrographs: x 100.)

FIG. 6x—After Still Further Creep at 300°C. (11.2% in 56 hr., 530 lb./in.²).

FIG. 6m—After Still Further Creep at 300°C. (11.2% in 56 hr., 530 lb./in.²).

is nearly uniform around the ring. The third feature is that the secondary reflecton spots do not sub-divide in turn, because it was found that the number of reflections on the ring became approximately constant; thus, it was the same at 11.2% as after a further 10% extension. Finally, close examination will show that an initial spot divides into some 10-20 units.

These changes may be interpreted without ambiguity. The breakup of the initial reflections means that the original grains subdivide into discrete units, each perfect in structure; these have been referred to already as "cells". The progressive scatter of the secondary reflection spots means that the orientation of these cells departs slightly but progressively from that of the parent grain, and therefore that the slow deformation involves the relative movement of the cells within the grains. Further, from the number of reflections on the diffraction ring in the steady state, it is possible to deduce that the size of the cells must be about 10^{-3} cm., or approximately 1/20th of the initial grain-size.

The changes shown by the microscope are equally significant. It will be noted that in the photomicrographs reproduced here the same group of grains has been kept under examination, making it easier to follow the changes at each stage of deformation. As with the X-rays, the changes are quite different from those found at room temperature. The main difference is the non-appearance of the systems of slip lines. The surfaces of the grains become rumpled and exhibit faint striations, but these have no similarity to slip lines, as comparison with the earlier Fig. 3*m* will confirm. A second feature of the higher-temperature deformation is the progressive thickening of the grain boundaries, presumably the result of differences in level caused by relative bodily displacements of the grains. Finally, some

evidence may be seen of migration of grain boundaries; but it should be added that this boundary mobility was not an important factor since in other specimens it was not observable. It may be concluded from these observations that the "slip-less flow," noted by Hanson and Wheeler is the mechanism whereby the grains deform by sub-division into the coarse cell formation.

Particular importance was attached to the further conclusion which could be drawn from the metallographic observations, namely that no recrystallization occurred during this deformation. The evidence was given conclusively by the observation that if at any stage in the deformation a specimen was repolished to remove all surface markings and then etched, the original grain boundaries would reappear. Therefore the cells are not grains finer than the original which have been formed by recrystallization; they are formed by direct sub-division of the grains. This is in keeping with the X-ray photographs, which in the early stages of deformation definitely show a splitting-up of the original reflection spots, as described already (Figs. 4*x* and 5*x*).

The fact that the same grain boundaries persist, means also that the changes in orientation of the cells within the grains are not so large as to cause the grain entirely to lose its identity. This explains, moreover, why the cells have not previously been found by metallographic methods, for it is difficult by etching to bring up boundaries between grains or parts of grains showing only small differences in orientation. In view, however, of the very definite X-ray evidence for the presence of the cells, special attempts were made to see if they could be observed optically. The orientation between contiguous cells, according to the X-rays, need not differ by more than 1°, although from one extreme of a grain to another it could differ additively by the order of 10°. However, careful optical examination of specimens in which the X-rays indicated a cell structure always showed that the initially polished surfaces developed a network of cells on the surfaces of the grains after deformation. An example is shown in Fig. 2; this corresponded

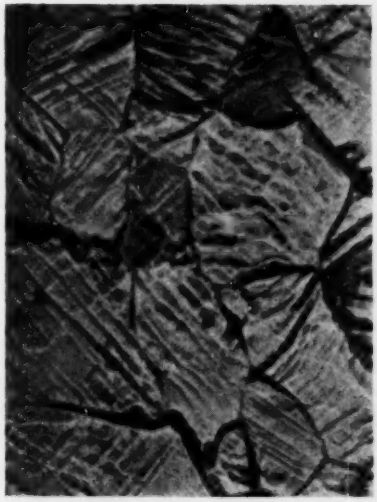


FIG. 2—Cellular Appearance in Grains After Slow 10% Extension at 250°C. Oblique illumination. x 100.

to a specimen, specially studied, which was extended 10% at 250° C. in 12 hr. by loading in hourly increments of 160 lb./in.^{2} In this specimen there were traces of widely spaced irregular slip lines, but in many of the grains the surface markings formed a cellular structure. The cellular appearance is clearly evident, specially if enhanced by oblique illumination as it was in this Figure. The interpretation of such surface markings is always difficult and the evidence is put forward tentatively. But it is significant that these markings

were only observable in the specimens where the cellular structure was proved by the X-rays; also that they corresponded to cells always of the same order of size, and that this size was the same as that indicated by the X-ray photographs. Moreover it is reasonable to expect that since relative movements at grain boundaries produced marked differences in surface levels, thus emphasizing the grain boundaries (as is obvious from Fig. 2), similarly, relative movements at the boundaries of the cells within the grains should also alter the local surface levels and emphasize these sub-grain boundaries.

Thus the X-ray and optical observations may be summed up by saying that, at a sufficiently elevated temperature and a sufficiently slow rate of strain, the familiar mechanism of deformation by slip passes over to a mechanism based on the relative movement of a much coarser cell structure into which the grains sub-divide. The X-ray evidence is quite clear on this point. It remains next to consider how the transition is affected at different temperatures and different rates of strain.

VI.—Deformation at Different Rates at One Temperature.

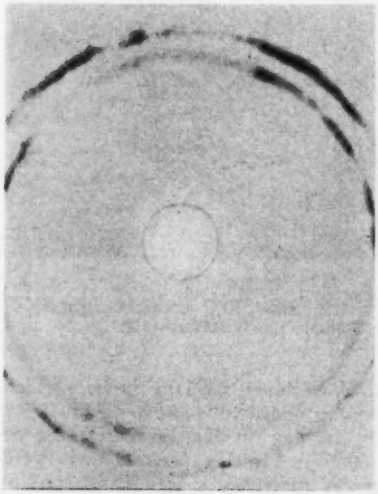


Fig. 7x—Changes After Rapid Extension at 250°C. (9.6% in 7½ min., tensile loading).

In this Section it is shown that the effect of increasing the rate of strain at a given elevated temperature is to produce a mixture of the high-temperature cell formation and the room-temperature crystallite formation; also that the amount of the latter increases with rate of strain and is accompanied proportionately by the reappearance of slip lines.

Fig. 7m—Changes After Rapid Extension at 250°C. (9.6% in 7½ min., tensile loading).

(Magnification of photomicrographs: x 100.)

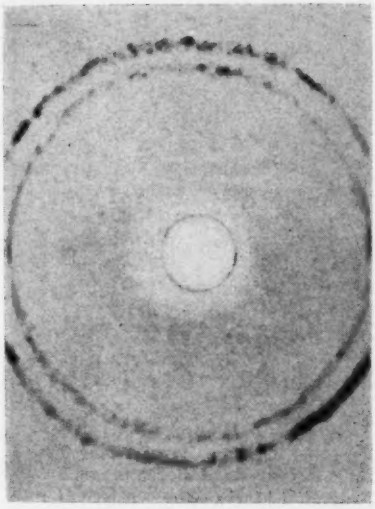


FIG. 8x—Changes After Slower Extension at 250°C. (10% in 12 hr., slow tensile loading).

FIG. 8m—Changes After Slower Extension at 250°C. (10% in 12 hr., slow tensile loading).

(1) Consideration is directed first to the following specimens which were extended at the same temperature (250° C.):

(*a*) a specimen extended 9.6% in approximately 7½ min.;

(*b*) a specimen extended 10% in approximately 12 hr.;

(*c*) a specimen extended 5% in 1060 hr. under a single initial load of 550 lb./in.²

The first two specimens were stretched by tensile loading in increments of 160 lb./in.², in the first case at 30-sec. intervals to a final stress of 2300 lb./in.², and in the second case at hourly intervals to a final stress of 1900 lb./in.²

The changes in the three specimens (*a*), (*b*), and (*c*) shown by the X-rays are reproduced respectively in Figs. 7*x*, 8*x*, and 9*x*. The corresponding changes shown by the microscope are given by Figs. 7*m*, 8*m*, and 9*m*.

The point at once evident from the X-ray photographs is that at the faster rates of strain the diffraction rings are composite. The numerous sharp spots indicative of the cell structure are superposed on the continuous ring characteristic of the crystallite formation. Therefore, both the mechanisms of deformation by slip and of deformation by the cell movement have been in operation. However, at the much slower rate corresponding to Fig. 9*x* the cell structure is predominant and a trace only of the continuous ring indicating the crystallite formation can be seen. Therefore at a sufficiently slow rate the cell mechanism only would be operative.

These points are confirmed by the corresponding photomicrographs. Thus systems of sharp slip lines are clearly evident in Fig. 7*m*, much less marked in Fig. 8*m*, and doubtful in Fig. 9*m*, which represents the condition of slipless flow associated with the cell mechanism.

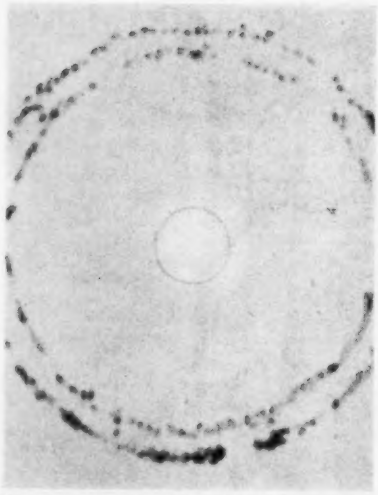


FIG. 9x—Changes After Much Slower Extension at 250°C. (5% in 1060 hr., creep under single load of 550 lb./in.^{2}).

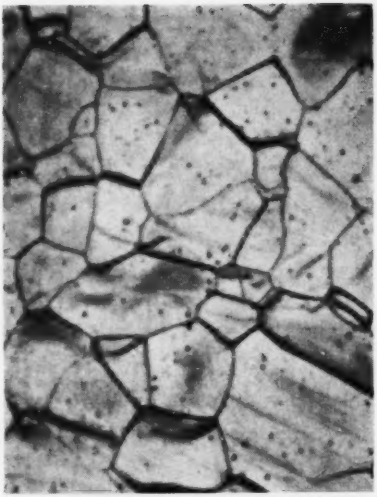


FIG. 9m—Changes After Much Slower Extension at 250°C. (5% in 1060 hr., creep under single load of 550 lb./in.^{2}). (Magnification of photomicrographs: x 100.)

(2) Specimens extended at the somewhat higher temperature of 300° C. are next considered. They showed, like the specimens described above, that at the faster strain rates both mechanisms were active, but at a sufficiently slow rate the cell mechanism of deformation only was operative. The effect of the higher temperature was that the latter mechanism predominated at higher strain rates than in the case of specimens tested at the lower temperature. In view of the general similarity to the previous results, it is unnecessary to reproduce further photographs, but the observations are summarized in Table I. The observations under the heading "structure" indicate the points

TABLE I.—STRUCTURE AND HARDNESS OF SPECIMENS EXTENDED AT 300° C.

Specimen	Load lb./in.^{2}	Duration	Extension, %	Structure	Hardness, D.P.N.
(*a*)	*	7 min.	10	Composite	17–19
(*b*)	*	9 hr.	10	Composite	....
(*c*)	520	97 hr.	6.6	Mainly cell	13.1–13.9
(*d*)	350	192 hr.	6.6	Cell	12.6–13.3
(*e*)	280	720 hr.	6.6	Cell	12.6–13.3

* Specimens (*a*) and (*b*) were extended by tensile loading in increments of 160 lb./in.^{2} at intervals of 30 sec. and 1 hr., respectively. The remaining specimens were allowed to deform continuously under the single initial load indicated.

already mentioned, that the cell mechanism predominates at the lower rates of strain, and somewhat sooner than at 250° C.

It will be noted that the final hardness figures measured on the specimens are included. These are of interest in showing that the specimens are harder as the proportion of crystallite formation in the structure is greater; also that at the slowest strain rates the hardness of the specimens is little, if at all, greater than the initial hardness of the annealed material, which was 12-13 D.P.N. These hardness figures are interesting because it has been shown in other work[6] that a metal becomes harder as the grains are fragmented by mechanical deformation into elements of decreasing size. Therefore the specimens in which the structure is composite must in fact consist of a mixture of "hard" and "soft" regions; the former corresponding to grains or parts of grains where the small crystallite formation is most pronounced, and the latter to other parts where the coarse cell formation is predominant. Specimens consisting entirely of the cell formation, on the same view, must be very little harder than the original material, as indeed was observed; for such specimens could be regarded as annealed material with a somewhat finer grain-size than the original, except for the fact that the cells have much the same orientation in each parent grain.

(3) Further experiments were carried out at the still higher temperature of 350° C. The specimens included:

(*a*) a specimen extended 9% in approx. 5 min. by tensile loading;

(*b*) a specimen extended 10% in approx. 4 hr. by tensile loading;

(*c*) a specimen extended at the constant rate of 0.01%/hr.

The first two were stretched, as before, by applying increments of 160 lb./in.^{2} every 30 sec. and every hour, respectively. The third was extended in the machine for forcing a constant strain rate.

Specimens (*a*) and (*b*) showed the composite structure and specimen (*c*) the cell formation alone. It was evident that the cell mechanism at this temperature tended to set in at faster strain rates than at the lower temperatures. Otherwise the results were similar to those at 300° C. and call for no further comment. Still higher temperatures were not used, in order to obviate the risk of introducing recrystallization.

In the above-described experiments on specimens deformed at different rates at a given temperature, it was necessary to decide if any vital significance could be attached to the point that the rapidly strained specimens were necessarily at the elevated temperature for a shorter time than those strained slowly. The possible effects of this factor could be studied by continuing to hold rapidly strained specimens at the same elevated temperature, in order to see if they developed a structure comparable with the slowly strained specimens. In no case did they do so. If the rapid straining had resulted in a composite structure with the crystallite formation greatly predominant, then the further heating produced recrystallization in occasional grains, but the recrystallized grains were much larger than the units of the cell structure. If the composite structure was one with the cell formation predominant, then the further heating caused no appreciable change in structure. Further heating of specimens in which the cell structure only was present caused no further change whatever. This means that, for the extensions and temperatures involved, the specimens in general were not deformed internally beyond the critical strain necessary for recrystallization and

grain growth. No doubt, such conditions could have been induced by much heavier deformation, but they would have confused the issues.

Thus, the results in this Section may be summed up by the general observation that the effect of strain at the elevated temperatures was to produce a composite structure in which the cell formation was more pronounced the higher the temperature and the slower the rate of deformation. A further conclusion is that the cell formation could be produced only when the straining and heating were applied simultaneously. This point is of some importance in view of those theories which regard creep as the result of a running balance between strain-hardening and "recovery". All that is known about recovery has been obtained from experiments in which specimens have been strained at room temperature and then examined for changes in properties and structure resulting from subsequent heating. The structural changes thus produced are quite different from those found in creep. The former involve first a breakdown to the crystallite formation and then some degree of recrystallization. The latter is characterized by sub-division to a coarse cell structure direct, and retention of the original grains.

VII.—Discussion.

Change in external shape of a specimen by mechanical deformation necessitates in practice a corresponding change in shape of the individual grains. This applies whatever the temperature or rate of strain.

In order to change shape a grain must divide into smaller elements so that one part may move relatively to the rest. At room temperature the elements are very small, and deformation results from relative translation of the elements between specific atomic planes, the so-called slip planes. At higher temperatures and slow rates of strain, the grains change shape by dissociation into much coarser elements, which, so far as can be judged, move relatively to each other without reference to specific slip planes. This appears to be the essential difference between the two modes of deformation.

Therefore, the new aspect to be considered in slow straining at elevated temperatures is the development in the grains of this coarse and irregular formation which, for the time being, has been described by the term "cell formation". However, before considering the actual process of deformation, it may be convenient to define more clearly the features of the formation as suggested by the X-ray and metallographic evidence already submitted.

Firstly, it would appear that the cell formation represents a definite sub-structure in the grains, analogous, in a way, to the sub-structure suggested by the slip lines in ordinary deformation at lower temperatures. This latter concept of a sub-structure tends perhaps to be hidden by the somewhat abstract theories of slip and dislocations which have been put forward by physicists in recent years, but it is quite fundamental to the slip process. It is more familiar to the metallurgist, having been brought out many years ago by the beautiful metallographic technique of earlier workers on plastic deformation, in particular by Rosenhain. This work showed that in deformation all atomic planes are not equivalent, but, in practice, only certain slip planes be-

come operative; these lie roughly about 10^{-3} or 10^{-4} cm. apart, and break the contour of a polished surface by macroscopic steps also of the same order of size; thus it is a common experience that slip lines during deformation do not multiply indefinitely but tend to a statistical separation. This points clearly to potential planes of weakness and therefore to a virtual substructure of the grains essential for the change of shape required by deformation. In the same way, it is considered that the cell formation corresponds to an equivalent and equally essential sub-structure; but one which, presumably because of the greater atomic mobilities at the higher temperatures, is coarser in size and less closely bound up with specific atomic planes.

A second feature to be considered is the relative crystallographic orientation of the cells within the parent grain. It was found just possible with the normal metallographic procedure of polishing and etching to obtain evidence of the sub-boundaries within the grains, but only with difficulty. Therefore the neighboring cells cannot differ greatly in orientation. On the other hand, the X-ray back-reflection technique, as already indicated, showed clearly a splitting of the reflections from the initial grains into secondary reflections during the slow deformation, and therefore proved definitely that some difference in orientation was developed. It is to be remembered that this technique is very sensitive; thus, in the conditions employed, a change in orientation of about 10° would move a reflection spot from one point on the reflection ring to a point diametrically opposite, or through 180°. The scatter of the secondary reflection spots, in the early stages of deformation when they could be followed, was over only a few degrees on the reflection ring. The corresponding scatter in the orientation of the cells within the grains would be only a small fraction of a degree. The metallographic and X-ray evidence together, therefore, show that the cells must have roughly similar orientations, but also that they must differ sufficiently in orientation to require boundary layers of atoms with transitional orientations. These layers will constitute sub-boundaries within the parent grain.

A third point to note is the progressive scatter in the orientation of the cells observed to occur during deformation. It is perhaps fortunate that such scatter does take place, for otherwise the discovery of the associated substructure would have been impossible even by the X-ray technique; also it would not have become evident that the change in shape of the grain involved the relative movement of the various parts of such a sub-structure. It is, however, a moot point whether the progressive scatter in orientations is an essential feature of the deformation process, and not a secondary effect arising from the inhomogeneous deformation inevitable in a polycrystalline aggregate. The important point is that the variations in internal orientation do make it possible to observe what is happening to the grain during the deformation.

The final point is that the parts of the sub-structure or cells appear to remain structurally perfect during deformation. This is shown by the observation that the secondary X-ray reflections from the cells are as sharp as the reflection spots from the initial annealed grains, and moreover remain sharp. This represents a difference from deformation by slip, which is supposed to result in lattice distortions and internal strains. If any such distortions occur during the high-temperature deformation by the cell mechanism they must be confined to the thin transitional layers of atoms at the cell boundaries. This point is of importance,

as discussed below, in relation to the degree of strain-hardening occurring during creep.

The above-mentioned points thus characterize the cell formation. In the more general case, of course, deformation will occur not only by the cell formation but also in some degree by the mechanism of slip and the finer crystallite formation. Both must be taken into consideration. It is suggested that the application to the problem of deformation at elevated temperature will then proceed along the following lines.

Firstly, it is to be noted that the breakdown of the grains to the small crystallite formation in the slip mechanism is accompanied by strain-hardening. This can be shown by experiment and also on theoretical grounds; it has been discussed fully in a recent paper by Wood and Rachinger.[6] Thus, Sir Lawrence Bragg[7] has shown that yield will tend to occur in a crystalline element when the elastic strain is of the order of d/l, where d is the atomic spacing and l the size of the element; therefore an element will stand a greater elastic strain before yielding as its size becomes smaller.

On the other hand, the dissociation of the grains to the much coarser cell formation will not be accompanied by appreciable strain-hardening because of the greater size of the cells. Some hardening may result because of the development of the associated subboundaries within the initial grains; but the hardening will not increase progressively with continued straining, firstly, because the cells do not become further reduced in size, and, secondly, and of equal importance, because their internal structure remains undistorted.

It follows that resistance to deformation at elevated temperatures, other things being equal, will be determined by the relative proportion and distribution of the two formations. If the cell formation predominates, then no appreciable strain-hardening will occur during deformation and the metal will flow continuously under stress as soon as any resistance inherent in the cell boundaries is overcome. Then we have quasi-viscous creep. So long as the cell formation is present in some degree in the metal there will be the possibility of continuous flow; but if the crystallite formation also is present and conditions of strain rate and temperature are favorable for production of the formation, each increase in deformation will tend to increase the crystallite formation at the expense of the cell formation; the crystallite formation will then tend to predominate and with it the associated strain-hardening until equilibrium with the applied stress is attained. Then we have transient creep. The rate of the quasi-viscous creep will depend on conditions at the cell boundaries and the effective internal stress, which may differ from the external stress according to the distribution of any crystallite formation present, an essential feature of the present view being the observation that the metal during deformation is to be regarded as a mixture of "hard" and "soft" regions.

It is realized that a complete study of creep must include other factors. Thus, any structural fault which becomes unstable under increase of stress or temperature will contribute to deformation. Also emphasis has been given rather to the part played by the substructure of the grains than by the boundaries of the grains themselves. This, however, is regarded as correct, because the grains in practice cannot change shape by grain-boundary movements alone; but for the possibility of the internal deformation by relative movements of the substructure, the metal would quickly part at the grain boundaries and so fracture. There are also the factors of grain-size as well as possible tendencies to recrystallization to be considered.

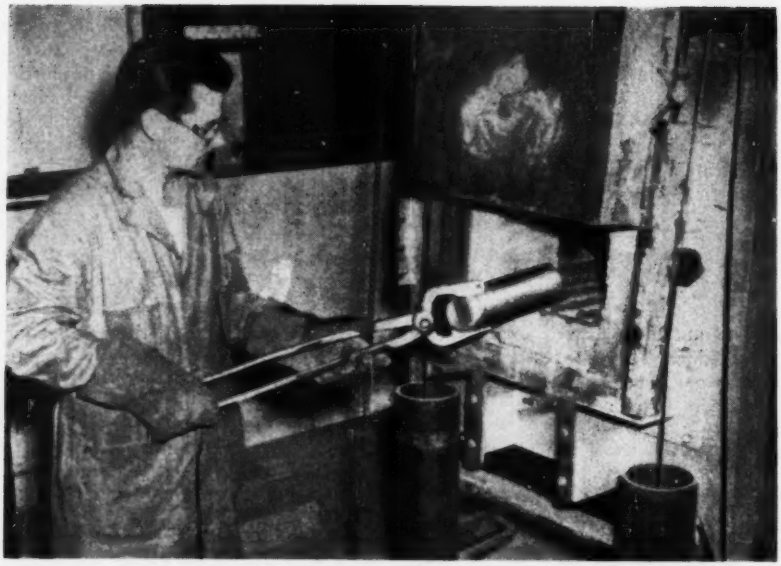
But the problem of creep can be made so complex that it appeared necessary to reduce conditions in the first instance to the simplest terms. This procedure seems to have been justified because it has brought out what must be the major systematic mechanisms involved in deformation, and their relation to temperature and rate of strain. The associated structural changes will provide a future basis by which the effects of the many practical factors involved in creep can be logically assessed and compared. This view is confirmed by further work in progress in which other variables have been introduced. In order not to make the present paper unduly long it is proposed to treat these aspects separately, but it can be stated that they indicate already that the above-described concepts of the sub-structure in the grains, with its related properties, allow a number of previously empirical and apparently unrelated phenomena to be fitted together into a systematic picture.

Acknowledgments.

The authors wish to express their indebtedness to Professor J. Neill Greenwood, whose extensive experience of creep phenomena was placed at their disposal, and to their colleagues in the Baillieu Laboratory of the University of Melbourne, with whom many points were discussed.

References.

1. E. N. da C. Andrade, "Proc. Roy. Soc.," 1914, [A], 90, 329.
2. E. Orowan, "J. West Scotland Iron Steel Inst.," 1946-47, 54, 45.
3. D. Hanson and M. A. Wheeler, "J. Inst. Metals," 1931, 45, 229.
4. W. A. Wood and H. J. Tapsell, "Nature," 1946, 158, 415.
5. W. A. Wood, "Proc. Roy. Soc.," 1939, [A], 172, 231.
6. W. A. Wood and W. A. Rachinger, "J. Inst. Metals," 1949, 75, 571.
7. W. L. Bragg, "Nature," 1942, 149, 511.



Commercially pure titanium metal is so strong that, in comparison with other metals, less of it is required to provide any specific strength. This ingot of titanium is about 40% lighter than one of stainless steel.

TITANIUM ALLOYS FOR AIRCRAFT

ACKNOWLEDGMENT.

This article is reprinted from the August 1949 issue of "Aero Digest." It was prepared by NATHANIEL F. SILSBEE, managing editor. He discusses the general history of titanium, lists some of its alloys, and mentions some results obtained by their use.

During the testimony for the 1950 budget, the Air Force revealed that it was counting on titanium to help break through the road-block which has been holding back jet-engine performance. Brig. Gen. Donald Putt, in charge of Research and Development on the Air Staff, said that: "Our materials problem is the major limiting factor in our present performance of jet aircraft and engines. . . . Much work has been done on high-temperature steels, including employment of alloying elements such as columbium and chromium. Titanium is coming into the picture very definitely. It has particular attractiveness because it is not a strategic material. There is a lot of it right in the earth around us."

Titanium was discovered over a century and a half ago when an Austrian chemist named Klaproth extracted a new element from an ore called *rutile*. He named it Titanic Earth, after the mythical Titans, sons of the earth.

A little later, big deposits of an ore combining iron oxide and titanium oxide were found in Russia's Ilmen Mountains; this ore was named *ilmenite*. Similar deposits were later found in the U. S. and Canada, Brazil, Africa, India and Australia.

Actually, titanium is the ninth most abundant element in the earth's surface layer, and is the fourth most plentiful metallic element suitable for structural use—only iron, aluminum and magnesium are ahead of it.

There is just one catch. The stuff is so darned "friendly" that it combines with many other elements and hangs on to them tenaciously to form oxides, nitrides and similar compounds. From the point of view of its being hard to separate, pure titanium has been classed by chemists as a rare metal.

Complicated Process.

Dr. Wilhelm Kroll invented the process that led to the commercial development of metallic titanium. Son of a Luxembourg blast-furnace director, Kroll, in the early 30's, discovered how to obtain ductile titanium by reduction with magnesium. At the outbreak of the war, he fled the Nazis and brought his intricate high-temperature vacuum metallurgy know-how to the U. S. Bureau of Mines.

In November 1946, the Bureau issued an information circular by R. S. Dean and B. Silkes entitled *Metallic Titanium and its Alloys*. This may be regarded as the start of the revised interest in titanium alloys. For many years prior to this, titanium has had an interesting and diversified history in its use as *pigments* in paints, enamels, plastics, etc., and very recently in optics, and as *gems* in jewelry. It is closely related to zirconium from which the brilliant "zircons" are derived.

Since publication of the 1946 circular, the Government and industry have spent some ten million dollars on titanium-metal research. In September 1948, du Pont announced the first commercial offering of ductile titanium in small lots. Remington Arms (du Pont affiliate) has put the metal on the market in sheet and bar form. It sells for $5 a pound in 100-lb. lots for remelting to ingot, and $25 a pound in the form of sheet and bar. These prices will be greatly reduced as the metal becomes commercially usable.

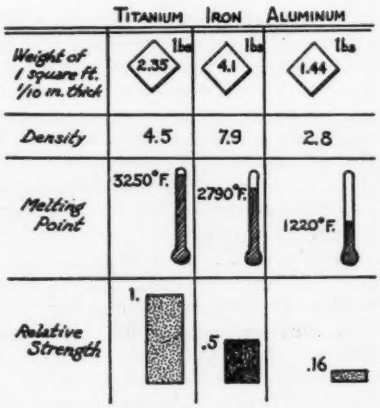
Also last fall, National Lead Co. took over the 40-year old Titanium Alloy Mfg. Co. of Niagara Falls, and has reported since the installation of a large, improved furnace for the expanded production of titanium beginning early this summer. National Lead also has what has been reported as the world's largest ilmenite mine in operation, located at Tahawus, in the northeast corner of New York State. More than a million tons of ore are mined each year, from which some 250,000 tons of ilmenite are obtained. During 1948, nearly 300,000 tons of ilmenite were imported from India, Norway, Brazil and Canada—most of it from India.

Look to Canada.

However, it is expected that the principal world source of titanium will shift from the sands of Travancore, South India, to Canada within the next three or four years. More than 125,000,000 tons of high-grade titanium-bearing ilmenite ore soon will be under development in the Allard Lake area of eastern Quebec. The discovery was recently made by Kennecott Copper Co., and a company called Quebec Iron & Titanium Corp.—two-thirds owned by Kennecott and one-third by New Jersey Zinc, its partner in the venture. From treatment of 550,000 tons of ilmenite ore per year, it is estimated that some 250,000 long tons of titanium oxide slag will be produced. First output is expected in 1951.

Switching back to Washington, the Committee on Appropriations was so interested in General Putt's remarks on titanium that they asked him to dig them up a statement presenting the basic facts regarding this new structural metal. The following extract will be of special interest in connection with this article:

> "The properties of titanium are favorable to extensive usage in both airframe and engine construction. The commercial metal is available at the weight of approximately 55% of that of steel and 1½ times the weight of aluminum. A strength-weight ratio, a property of primary interest to aeronautical engineers, better than that of the best aluminum alloys, has been obtained in laboratories. Titanium has a melting point of 3250° F. about 2½ times that of aluminum or magnesium and somewhat higher than that of iron. This characteristic is important since the materials will retain satisfactory structural strength at temperatures reached in supersonic flight due to aero-dynamic heating and at which aluminum alloys become worthless."



Properties of Commercially Pure Elements

The business of incorporating titanium into alloys for use in aircraft gas turbines started on a relatively small scale some years ago. One of the first alloys was K42B, developed by Westinghouse Research Laboratories, containing 42% nickel, 22% cobalt, 18% chromium, 2.50% titanium and 15.5% iron. Cobalt and chromium are critical materials, likely to be more so in the light of recently revealed figures showing a sharp drop in Russia's export of these to the U.S.

Better Alloys.

K42B, although a useful alloy in blades for superchargers and gas turbines in its day, is now regarded as on the way out. Some of the newer Westinghouse alloys include about the same percentage of titanium. *Refractaloy 26*, for example, has about the same amounts of cobalt and chromium, less nickel, and adds 3%-plus of molybdenum. *Discaloy 26* contains 2.33% of titanium. International Nickel's *Inconel W* has about 75% nickel, 14% chromium, almost 3% titanium, and is used for combustion chambers of jet engines.

The famous *Nimonic 80* (and 80A), used in all British turbojet and turboprop engines and made by INCO's

subsidiary, Henry Wiggin & Son, contains 2.44% of titanium. A German high-temperature alloy known as *Tinidur* contained 30% nickel, 15% chromium, 1.7% titanium—no cobalt as they didn't have any—and most of the balance iron. It was used for jet engine blades (or buckets), nozzles, and other high-temperature service.

All of these are forgeable or wrought alloys, with a fairly high chromium content. Those alloys used for making turbine buckets and nozzle diaphragms by precision investment castings (such as Austenal's *Vitallium*) do not contain titanium, but almost invariably have molybdenum.

A decision by the military to specify titanium-rich alloys in certain articles now under test would give the program a shot in the arm. Considering titanium's ability to substitute for stainless steel (with 40% less weight) in an emergency, its rapid development would be a good national investment. A step in this direction may be seen in the recent establishment of project CP-10-NASC by AIA's National Aircraft Standards Council, at the request of the Armed Services. This is for an AN (Air Force-Navy) specification for titanium; Lockheed Aircraft will act as sponsor of the project.

We have reserved for final mention what may be the most promising use of all for titanium in connection with jet-engine turbine blades—its use in one of the "ceramals." (This composite word —*ceramics-metals,* is sometimes referred to as "ceramets.")

A Hot Proposition.

The aircraft gas turbine is essentially a heat engine. Therefore, the greater the heat, the greater the power. The present limits of gas-turbine blades are a reasonably long operating life as gas temperatures up to 1500°F., with very short runs permitted up to 1700° or 1800°F. The immediate goals of current research on gas-turbine blades is for longer life in the 1500° to 1800° bracket; a practical life at temperatures of 1800° to 2600°; and a short but useful life at temperatures above 2600°.

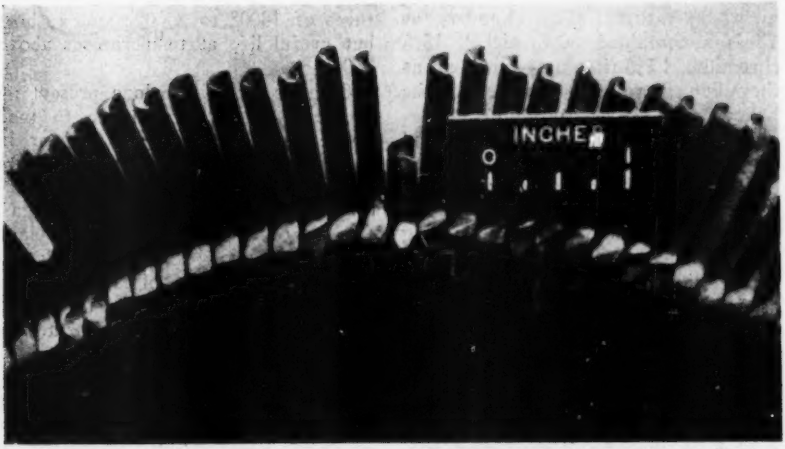
Ceramic materials alone present no problems in heat resistance to well above 3000°F., but they are poor in thermal-shock properties—the ability to withstand severe and abrupt temperature fluctuations of the surrounding gas. On the other hand, gas-turbine blade alloys have good thermal shock resistance, but their high-temperature operation is limited by the melting point of their lowest melting constituent. The combination of the two in ceramals is therefore quite logical.

Cemented carbides have been widely used in the tool industry for a number of years. Research on the application of ceramics for gas turbines was begun in Germany during the war by Dr. R. Schmid, and his findings are embodied in a report translated by the Air Material Command, *Ceramic Materials for Machine Parts Exposed to High Heat.*

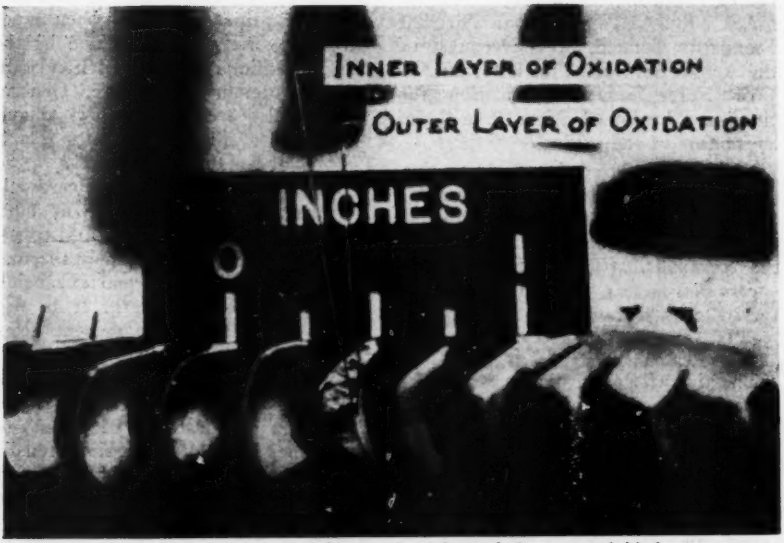
Work in this country has been under way since the war, conducted by the NACA, National Bureau of Standards, Battelle Memorial Institute, General Electric Research Laboratory, Champion Spark Plug's ceramics plant, Detroit, and many other places.

One of the most promising ceramals is a carbide-type, consisting of 80% titanium carbide (TiC) and 20% cobalt (Co). This material has a high thermal conductivity, a low thermal expansion and good tensile strength. It is also lighter than any of the present heat-resistant alloys.

An investigation of this ceramal was conducted at the NACA Lewis Flight Propulsion Laboratory, Cleveland to determine its (*1*) short-time tensile strength (1800 to 2200°F.); (*2*) thermal-shock resistance (1800 to 2400°F.); simulated service performance characteristics from 10,000 to 17,500 rpm and inlet-gas temperatures



In phase 2 of simulated-service performance test, first ceramal-blade failure took place after 12 hrs. 13 min. operation, after 108 metal blades had failed.
Close-up of ceramal blade failure.



View from top showing fractured surface of the ceramal blade.

between 1700 and 2200°F. A complete report of the results of this investigation is found in *NACA Technical Note No. 1836 (March 1949), Initial Investigation of Carbide-Type Ceramal of 80-Per Cent Titanium Carbide Plus 20 Per Cent Cobalt for Use as Gas-Turbine-Blade Material.*

Although the tensile-strength and thermal-shock tests were generally satisfactory, the results of the so-called Quasi-Service Evaluation were of special interest. In phase 2, a total of 12 hours and 13 minutes of operation were completed at turbine speeds of 10,000 to 15,000 rpm, and 2200°F. At the ends of this time, service failure had taken place in 108 metal blades (including four replacement and eight control blades) but only in *one* ceramal blade. During the repeated shutdowns for metal blade replacements, one of the ceramal blades was accidentally broken and a second underwent disk-dovetail failure. This simply indicates that more care will be required in handling carbide-type ceramal blades than with metal-alloy blades.

The successful passing of the first severe test by this TiC 80/ Co 20 carbide-type ceramal was the first step in the new program. Further tests with variations in the combinations and proportions of the constituents are expected to result in even more satisfactory ceramals for jet-engine turbine blades.

As Abe Silverstein, the brilliant research director of NACA's Flight Propulsion Laboratory put it in the 12th Annual Wright Brothers Lecture, *Research on Aircraft Propulsion Systems*: "Research on ceramals may result in a more fruitful and rapid development of refractory materials than work on the pure metals."

Some very recent tests as the Lewis FPL, Cleveland indicate that the boys are really on the right track.

DIESEL ENGINES AND THEIR FUELS

ACKNOWLEDGMENT

This article by P. N. EVERETT of the Anglo-Iranian Oil Co., is reprinted from the "British Motor Ship" for October, 1948. It discusses the problem of grades of fuels for high speed and slow speed machinery. The article is an excerpt from a paper presented to the Joint Conference of the Institute of Fuel and the Institute of Petroleum on September 23, 1948.

The Diesel engine came into being and into favor on two points, first, its wonderful thermal efficiency and, secondly, its ability to burn cheap, low-grade liquid fuel. This paper is confined to a discussion of these two points. The thermal efficiency has gradually improved and there is little more to do in this direction, but the second point has been woefully neglected. The first Diesel engine put to work in this country was only 35 b.h.p. and ran on Texas fuel oil of .922 specific gravity. That was in 1902; to-day, after 46 years, almost all engines in the country are supplied with a 100 per cent distillate fuel, and there are motor ships, mostly Scandinavian, having engines of 6,000-8,000 h.p. requiring gas oil.

THERMAL EFFICIENCY.

The main types of heat engine in use or under development to-day and designed for burning heavy liquid fuels are given in Table I, which shows the relative position of the Diesel engine. Thermal efficiency must be qualified by the price structure of the fuels required to give reliable service. For instance, if the Diesel engine needs fuel at 100s. per ton and gives 40 per cent thermal efficiency, then the gas turbine at a thermal efficiency of 32 per cent would need to use fuel costing 80s. per ton to give equal performance. Price varies according to locality and quality but mainly the latter, and the problem becomes: What is the lowest grade of fuel on which any type of heat engine can operate with reliability at continuous full-load conditions in service? The expression "bunker fuel C grade" has been heard so often lately that it might be useful to state that the only quality figures quoted in this specification, which has been renamed Grade 6, are:—

TABLE I.—LIQUID FUEL HEAT ENGINE DATA.

	Steam Turbine	Open Cycle Gas Turbine	Closed Cycle Gas Turbine	Hot Air Engine	Free Piston Generator and Turbine	Diesel Engine
Combustion Space	Boiler	Combustion Chamber	Air Heater	External Burner	Cylinder	Cylinder
Medium used in Cycle	Water-Steam	Air-Gas	Air	Air	Air-Gas	Air-Gas
Apparatus Employed	Boiler Superheater Turbine Condenser Auxiliary Pumps	Combustion Coamber Compressor Heat Exchanger Turbine	Air Heater Compressors Heat Exchanger Turbines Intercooler Auxiliary Pumps Supercharger	Burners Engine Regenerator	Free Piston Units Turbine Auxiliary Pumps	Engine Auxiliary Pumps Supercharger
Internal or External Combustion	External	Internal	External	External	Internal	Internal
Max. Temperature in Cycle	850° F.	1150° F.	1200° F.	1200° F.	3000° F.	3500° F.
Max. Pressure in Cycle	475 lbs./sq. in.	45 lbs./sq. in.	415 lbs./sq. in.	570 lbs./sq. in	1250 lbs./sq. in.	750 lbs./sq. in.
Thermal Efficiency Approx. for 6,000 B. H. P.	25%	27%	31% (estimated)	33% (estimated) small units only	38% (estimated)	39%

Flashpoint, min. 150 degrees F.; viscosity at 122 degrees F., max. 300" Saybolt Furol (i.e., about 6,500 Redwood 1 at 100 degrees F.); water and sediment, max. 2 per cent (sediment, .25 max.).

When offering bunker fuel for a marine steam-boiler installation the quality is frequently described as "not inferior to C grade." This can be, and actually is, anything, often being a mixture of residues from several refining operations, as the specification was designed to give the least possible restriction to supplies. Steam installations can work with satisfaction on these fuels, as we know from many years' experience. As yet we have no corresponding experience of such fuels in any of the other types of heat engine.

Owners of Diesel engines usually call for a better and more expensive grade known as Diesel fuel and, as mentioned, its price must be taken into account when assessing the value of the thermal efficiency.

GRADES OF FUEL.

The three grades of fuel in which we are interested are known as gas oil, Diesel fuel and fuel oil.

Gas oil is 100 per cent distillate with minimum volatility requirements.

Fuel oil is the residual oil after all usable distillates have been removed.

Diesel fuels may be a distillate of lower volatility than gas oil from certain refinery processes or from special crudes, but as such supplies are relatively scarce the bulk of the Diesel fuel is made from a blend of gas oil and fuel oil.

Roughly, fuel oil represents about 45 per cent and gas oil 15 per cent of the crude, but these figures will vary with different crude oils and refinery operation.

All people in the oil industry know that today there is a grave world shortage of gas oil, but this fact does not appear to be fully realized by engine builders. It is safe to say that the general trend of engine development during the past 20 years has necessitated a continual improvement in fuel. To get higher power, higher speeds and a larger number of smaller cylinders have been used; b.m.e.p. has been pushed up to the smoke point after resort to one type of some high-grade fuel and, at the same time, the fuel injection has been simplified and cheapened. This state of affairs will hold so long as engine builders continue to use only high-grade distillate fuels, not only on the test bed, but also for developing new types, in spite of the fact that they hope to sell 90 per cent of their output for export to countries where gas oil is often unobtainable. A user can buy fuel oil only if his engine is designed to burn it. The first cost of the engine and its maintenance will always be a little higher, and therefore there should be a suitable price difference to encourage the engine builder to design his engine to burn fuel oil and the user to buy fuel oil. Supply and demand among the many grades of petroleum products, together with new refining methods, may alter the price difference between gas oil and residual oil, but residual oil will always be both more plentiful and cheaper. Further, when the new pipelines and refineries are in full operation there may be ample supplies of all grades available, but residual fuel will still be cheaper.

It is well known in the petroleum industry what products come under the headings gas oil, Diesel fuel and fuel oil, and each product is, in fact, produced to fairly close specifications, depending on the refinery, but it is quite another matter to give a set of detailed figures which will suit all refineries—in fact, it is impossible. Each oil company must market what it can most economically produce from the crude flowing from the wells from which it draws its supplies.

Many specifications for these fuels are in existence, but it will suffice to refer to British Standard Specification Nos. 209 and 742, 1947 editions, which also include the methods of test.

It is suggested that three grades of fuel are required to meet the varying demands of the Diesel engine:—

(a) A gas oil suitable for high-speed Diesel engines in road vehicles. This fuel would be supplied to all engines with small cylinders and high r.p.m. Also to all engines where the r.p.m. and load are continually varying, and where there is much idling, and yet good acceleration is necessary, such as railcars, shunters, Diesel locomotives, cranes and excavators, irrespective of size.

(b) An intermediate fuel suitable for medium-speed engines on steady load, such as driving electrical generators or coasting vessels.

(c) A residual-type fuel for slow-speed engines of large cylinder diameters.

The Engine Problem.

Table II gives data of interest to a study of the subject. It concerns four engines, a 100 h.p. lorry engine, a 1,200 b.h.p. railway engine, a 1,200 b.h.p. stationary engine and a 3,200 b.h.p. marine engine. These four engines give an indication of the varying engine requirements when considering

TABLE II.—TYPICAL ENGINE SIZES.

Actual engines in service but data estimated from modern practice.

All four cycle airless injection engines.

* Recess assumed hemispherical for calculation purposes.

	B.H.P.	R.P.M.	No. of Cyl.	Cyl. Dia. inches	Combustion Chamber V Clearance Volume cb. ins.	Combustion Chamber inches	Combustion Chamber S Surface sq. ins.	S/V	Fuel Injected per Cycle per Cylinder cu. in.	Fuel Injected per Cycle per Cylinder Diam. as a Sphere inches	Approx. Size Holes in Injector inches	Approx. Time for Injection and Combustion seconds	Fuel per hr. per sq. in. Cyl. Cross Section lbs.
1	100	1700	6	4.5	5.9	2.75	38.2	6.48	0.00455	0.206	.010	.003	.438
2	1200	750	12	10	83	6.7	194	2.34	0.055	0.472	.016	.007	.482
3	1200	300	8	17	432	11.5	566	1.31	0.187	0.71	.018	.019	.238
4	3200	115	8	25.6	2410	20.5	1380	.57	1.40	1.35	.032	.051	.303

fuels A, B and C. Engines 1 and 4 are representative of engines in mind to use fuels A and C respectively. Engines 2 and 3 are of the same power, but No. 2 would use fuel A and No. 3 fuel B.

A point to bear in mind is that a motor ship may have a large main engine of the slow-speed type and small auxiliary generator engines of the high-speed type, but it is unreasonable to let the small-power engine settle what fuel the main engine shall use.

The troubles experienced in burning liquid fuel in a Diesel engine, in general, are the same for all types of engine on all grades of fuel. The first symptom, usually, is failure to carry the correct load and r.p.m. without smoke at the exhaust, and, as far as the fuel and its method of use may be the origin, the cause can invariably be traced to:—

(1) Faulty injection, producing nozzle carbon.

(2) Faulty combustion.

(3) Loss of compression from sticking piston rings, exhaust-valve leakage or cylinder-liner wear.

These things are interconnected; for example, a faulty injector will permit carbon to build up, giving a faulty spray, producing bad combustion, which causes valve failure and sticking piston rings and so liner wear, with loss of compression, which, again, causes faulty combustion. When both the engine and fuel are the best we can today produce, then the limiting features for endurance are the sprayer and the piston ring.

FUEL CHARACTERISTICS.

Specific Gravity.—This is only quoted by the oil companies to enable conversion to be made from weight to volume or vice versa. It has no effect on combustion, but in changing to a fuel of different specific gravity it is necessary, for the same power, to inject into the cylinder at each stroke the same weight of fuel. The volume will be inversely proportional to the specific gravity. This is no detriment when, as is usual, fuel is purchased by the ton. If by the gallon, then there is the slight compensation that lower gravity indicates higher calorific value.

Calorific Value.—This varies very little between the grades, probably 3 to 4 per cent, gas oil being highest. The measurement of calorific value needs experience, but it is pointed out that calculation of the calorific value is quite accurate and may be used for most purposes. Then there is the question of gross and net value arising from the fact that in the former, as measured in the calorimeter, the water formed from the hydrogen during combustion in oxygen is reduced to the liquid state, whereas the latter applies to the practical application of the combustion of petroleum products, where usually this H_2O escapes in vapor state. The difference represents the latent heat of condensation of the water formed and its value recommended by Heat Engines Trials Committee of the Institution of Civil Engineers in 1,055 B.T.U. per lb. This difference makes an appreciable variance in the calculated thermal efficiency. The practice in England and the United States is to use the gross value. In some Continental countries, including Switzerland, the net is used. Care should be taken to know which has been used in establishing a thermal efficiency. In ordinary practical-shop engine tests it is very difficult to detect any difference in fuel consumption or output arising from slight differences in the calorific value of gas oil or Diesel oil.

Pour Point.—This is a measure of the lowest temperature at which the fuel flows, and the test which has become standard in the U.K. is the A.S.T.M. It gives a higher reading than the set point (IP) which, to the writer, appears the better test as a pressure is applied to the fluid. The pour-point requirement of a fuel is entirely decided by the service in which it is used and whether heating is available permanently, although it should be understood that the provision of heating facilities is usually determined by the viscosity and not the pour point.

Acidity.—Acidity may occur from inorganic acid used in the refining process, but it is very rare that this finds its way into gas oil or Diesel fuel.

Sulphur.—Sulphur is the whipping-boy for the Diesel engine. No matter what happens it is attributed to the sulphur compounds in the fuel. Hot corrosion, cold corrosion, lurid stories of concentrated strong acids, pitting of exhaust-valve seats, carbon on injector nozzles, cracking of cylinder liners, stuck piston rings, liner wear, have in the past 20 years all been recounted personally to the writer by engine builders or fuel users as being due to sulphur. Sulphur occurs in the crude oil in varying forms, but by the time the fuel has passed through the refinery it is associated with the fuel in compounds which chemically cannot cause corrosion of any ferrous parts with which the fuel may come into contact. When fuel containing sulphur burns, the sulphur is changed into oxide, which, again, is quite free from corrosive effect, and since conditions inside the cylinder very rarely fall below the dew point, there is little chance of condensation. When an engine stops there are invariably many revolutions with the fuel cut off, when only air is drawn in, which clears out all combustion gases. It is significant that the present criticism of sulphur comes from the U.S.A. and Scandinavia, while other countries are using present-day fuels with marked success.

Ash, Sediment and Water.—These items can be common to all fuels and affect all types of heat engines. As a rule the amount increases with increasing viscosity of the fuel. Sediment is adventitious and consists of fine particles of scale from tanks and pipes, road dust from air drawn into storage tanks, and contamination generally arising from the handling of the fuel in barges, rail and road tank cars, and includes any carbonaceous matter. Water is also adventitious and comes

by condensation from the air drawn into storage tanks and might arise from leakage in the case of ship's tanks. Oil companies are aware of all this and go to considerable trouble and expense to reduce all adventitious matter to a minimum, but this cannot always be said for the user. Storage arrangements, including design of tank and its fittings, is an important matter, also all fuel tanks should be cleaned periodically. Most of the adventitious matter can be removed by settling, filtering or centrifuging, according to the quantity involved, the time element and the viscosity. Ash is a more serious item and is what remains after all the fuel is burnt. It includes adventitious sediment too fine to be removed by the usual cleaning gear and the ash dissolved in the fuel in the form of organic salts of various metals and, perhaps, salt or soda, but no carbonaceous matter. When the fuel burns, these substances are turned into oxides, which are held in suspension in the combustion gases. It is, therefore, essential that the ash content be as low as possible for all heat engines using internal combustion. Diesel fuel should always be centrifuged, and to facilitate the process it should be heated to about 100 degrees F. and passed very slowly through the machine. Cleaning fuel oil is more difficult and will be referred to later.

Viscosity. — Viscosity is connected with fuel consumption in that it ultimately decides the size of the fuel particle that mixes with the air prior to combustion. This size of particle also depends on diameter and length of hole in the nozzle and the fuel pressure. It is necessary to get the correct balance between penetration and pulverization to suit the size of cylinder, shape of combustion chamber and degree of turbulence available. This problem is solved by trial and error on the test bench. It is not so vital with gas oil as with a residual fuel. It is the viscosity of the fuel, together with size of hole, which determines the injection pressure in the fuel line. This is why it is so difficult to design a satisfactory spring or accumulator injection system to use any grade of fuel. In the case of fuel oil, the viscosity should be reduced to at least 200″ R.I. by heating.

The remaining fuel characteristics for consideration are distillation range, carbon residue, hard asphalt and cetane number, and these will be dealt with together under the headings of fuel requirements for (i) High-speed Engines, (a) (ii) Medium- and Slow-speed Engines, (b) and (c).

High-speed Engines.

Everyone is agreed that automotive engines running in the crowded streets of our great cities require a good fuel, but our quest must not lead to recommending a fuel which is such a small selected cut of the crude that it is scarce and, therefore, in short supply. Such a fuel would not only be expensive, but difficulty would be experienced in suddenly expanding supplies to meet the needs of a major war. Pool grade gas oil used in England during recent years would appear to give the desired service when one watches carefully the performance of Diesel buses in our big cities, such as London, Leeds and Manchester, and also the long-distance heavy lorries on cross-country runs. The engines of these vehicles are designed and built by about eight different British builders, but all of them are direct-injection open-chamber types. The fuel consumption is exceedingly good and the exhaust usually free from smoke. Pool gas oil is practically free of asphalt and its Conradson value is only a trace, therefore cetane number and distillation range or volatility are

the only items now left for consideration. Cetane number is still the best yardstick by which to measure the suitability of gas oil for high-speed engines. The highest figures found today in petroleum gas oils, namely, 56 to 58, have actually been found to be optimum values and there does not appear to be any advantage in going higher. Provided a fuel is 100 per cent distillate, of low viscosity with corresponding volatility and high cetane number, then its distillation characteristics, either at the beginning or the end, are not found to be of any great importance in practice, although if the fuel has a low cetane number then high volatility at the beginning of the range can assist starting, and if the engine has poor combustion characteristics then high volatility at the back end will be helpful. But the lighter the fuel, the lower is availability and the higher the cost. American engines in the early days ran on a heavy kerosene, and from what we hear some American builders would like to return to a similar fuel. The writer feels, however, that this trend is rather a reflection on design.

A further point in connection with this demand for a better gas oil is the fact that the engine of the near future for transport work would appear to be the supercharged four-stroke engine. There is every indication that these engines are much less fuel-sensitive than normal four- and two-stroke engines. The figures suggested as being suitable for an automotive gas oil are:—

Specific gravity..... Not less than .83
Initial boiling point. About 200 deg. C.
Final boiling point..About 350 deg. C.
Cetane number..... 48 to 58
Sulphur..... Max. 1.5 per cent

With most gas oils today, the higher the cetane number, the higher the pour point, although there is no actual relationship. The pour point is a matter of the paraffin-wax content.

Medium- and Slow-speed Engines.

Engines for duty (b) and (c) can be dealt with together, as it becomes a question of the extent to which "fuel oils" can be used, considering cylinder diameter, r.p.m. and load conditions. The nature of the fuel, that is, whether it is paraffinic or asphaltic, is very important. The distillation range by itself gives little useful information, but what is left after final boiling point, i.e., its percentage and its properties, are important. These vary considerably with different crudes and the complete combustion of this residue constitutes the problem. The carbon residue, as expressed by the Conradson value, is a measure of this property of the fuel to some extent, but from the engine point of view the Conradson value is unsatisfactory.

The real difficulty in burning residual fuel is to consume the hard asphalt, which is a bituminous substance probably of high C/H ratio, in colloidal solution in the fuel. It is not possible to remove it by filtration or centrifuging. The burning of hard asphalt depends on breaking up the fuel as fine as possible and applying as much heat as is feasible—that is, high compression and compact combustion chamber.

Cetane number is not very important in slow-speed engines but it can, if too low or if the engine compression happens to be low, make starting difficult and give heavy knocking, which is so objectionable. Further, if by any chance a fuel sprayer permits solid fuel in its jet, then the lower the cetane number, the more chance of the fuel reaching the piston top or the cylinder liner before combustion is completed and the burning droplets will be extinguished with formation of carbon.

The burning of fuel oil in a Diesel engine involves:—

(a) Cleansing the fuel of all water and adventitious matter.

(b) Correct combustion chamber, pump and injector.

(c) Adequate cooling of the injector tip.

Cleansing the Fuel.—The best system is centrifuging and, where the expense is justified, double centrifuging; the first centrifugal is set to take out the water and coarser matter and the second one to take out the very fine solid matter. This system was introduced into the motor ships of the British Tanker Co. about 20 years ago and found very beneficial. Pipe diameters should be much larger than for distillate fuel. Correct storage facilities are vital. Bad arrangements are the cause of much trouble even today.

Combustion Chamber.—The combustion chamber must be shaped to suit the spray and the correct intensity and direction of turbulence provided. Residual fuel must be broken up finer than gas oil, and this may need more holes in the sprayer, but their distance apart must be sufficient to prevent the edges of the sprays coalescing into solid fuel. The fuel should on no account come in contact with the cylinder-liner wall.

Fuel Pumps—Fuel oil should be injected at a quicker rate into the cylinder than gas oil. To control pump delivery, most modern engines use a helical recess cut in the plunger, working over a port and the plunger twisted by rack and pinion. This design has much to commend it, particularly for a multi-cylinder engine, and is very old, being used on some pre-Diesel British oil engines. When the modern high-compression airless-injection engine appeared engine builders designed and made their own pumps. A mechanically operated spill valve was the popular design, and with this design it appears possible to get the same fuel consumption with a lower ratio of maximum to compression pressure in the cylinder and, in the writer's opinion, less likelihood of bleeding at the injector. But this type of pump was discarded by most firms on account of its cost and the difficulty in service in a multi-cylinder engine of keeping all pumps to equal adjustment, due to wear on the tappets, etc., but this should not apply to a large, slow-speed engine. The C.A.V. retracting delivery valve is a good help against bleeding at the injector. With all pumps using heated fuel it is advisable to put the suction under a pressure of 20-30 lb./sq. in. by means of a boost pump.

Injector.—Many things are involved. The design, the materials of construction, the accuracy of initial manufacture, the quality of maintenance. The seat separate from the guide is to be preferred, with the guide away from the seat to give cooler operation and more flexibility. The needle should be as light as possible and the tunnel between the seat and nozzle holes as short as possible. The guide, needle and seat should be of different materials, cast iron, case-hardened steel and a high carbon steel being suitable. The required accuracy of the fit of the needle in the guide is not measurable, and while certain firms do make them interchangeable it is not necessary as they cannot stay interchangeable in service. The needle and guide should each be lapped to a master before being lapped together. Quality of maintenance cannot be over-estimated, but it is very difficult to obtain the requisite standard in service. This high standard is necessary to prevent the least trace of bleeding at the needle. In examining typical examples of injectors for high-, medium- and slow-speed engines it will be noticed that they are all spring-loaded needle valves, which open automatically when the fuel pressure in the inlet pipe reaches a predetermined figure. The best design to prevent bleeding is the mechanically operated valve, such as fitted to the Doxford engine, which probably burns residual fuel more successfully than any other engine in the world.

Cooling of the Sprayer Tip.—This is most important and can be helped con-

siderably by the design of the component parts being arranged to convey the heat away. Cooling, to be efficient, must be right at the nozzle tip. The best design is that used in the Doxford engine. Cooling is very thorough and the medium, water in this case, is brought very close to the fuel as it is entering the cylinder. The cooling space of a sprayer can be circulated with water or fuel oil—lubricating oil has been tried but found unsatisfactory. Fuel oil having only half the specific heat cannot be so efficient as water, and to get the best effect water must be used. Corrosion can be prevented by suitable treatment of the sprayer parts or by an inhibitor added to the water. The position of the sprayer in the cylinder head with reference to the combustion chamber is important, and when deciding this arrangements should be made to direct the flow of the incoming cylinder-head cooling water on to the place where the sprayer is located.

The maximum output of a Diesel engine involves b.m.e.p. A four-valve four-cycle unsupercharged engine can carry a b.m.e.p. of 90 p.s.i. and on the test bed a supercharged four-cycle engine can carry 200-300 p.s.i., but few people would care today to buy an engine for continuous output rated at over 120 p.s.i.; the limit is the life of the top piston ring, together with its lubrication. An engine burning heavy fuel is bound to be a hot engine, and therefore the conditions in which the top ring works will be even worse. There is a real and urgent need of research work on the life of the piston ring.

It is worth recording that remarkable development of the Diesel engine has been almost entirely by way of private enterprise under peace conditions, it having missed the intense research, paid for by the Government, which two major wars made necessary in the case of the petrol engine and the gas turbine.

It should be emphasized that 20 years ago many British engines as small as 50 h.p. per cylinder were running successfully on fuel with a hard asphalt content of 1.25 per cent, while many modern engines of this size today have difficulty in running on a fuel with only the 0.25 per cent hard asphalt. Today there are motor ships with large double-acting two-stroke engines of, say, 8000 b.h.p. requiring gas oil. Such a ship is using fuel at the same rate as a fleet of 1000 Diesel lorries and the same quality fuel. Surely, if the big Diesel engine is to survive competition with other forms of heat engine it must revise its fuel demands.

References.

"The Diesel Engine," H. A. de Clark, Inst. of Mech. Engineers. 1903
"Fuel Characteristics in Relation to Pump and Spray Design," L. J. Le Mesurier and R. Stansfield, Diesel Engine Users Assoc. 1933
"Some Observations on Fuel for Heavy Oil Engines," L. J. Le Mesurier and R. Stansfield, Inst. of Marine Engineers. 1934
"Diesel Fuel, its Characteristics and Use in the Engine," P. N. Everett, Zirkel Englisch Sprech. Ing. (Berlin). 1934
"Design of Fuel Injectors for Diesel Engines," G. J. Lugt, Inst. of Petroleum Technologists. 1936
"Some Types of Propelling Machinery Available to Ship Owners," C. C. Pounder, Inst. of Mech. Engineers. 1943
"Use of Heavy Oils in Stationary Diesel Engines," M. Zwicky and H. Riggenberg, Sulzer Technical Review. 1946
"Cooled Injectors and Pilgrim Injection System," J. J. Broeze and G. Scherpenhuysen, "The British Motor Ship." 1947
"Burning of Boiler Oil in Marine Diesel Engines," J. Lamb, Inst. of Marine Engineers. 1947

METALLIZING IN RELATION TO MARINE ENGINEERING

ACKNOWLEDGMENT

This article by J. BARRINGTON STILES, M. I. Mech. E. who is with the Metallizing Equipment Co., London, England is reprinted from "Transactions of the Institute of Marine Engineers, Vol. LX, No. 12 (1948)." It discusses the application of the metallizing process both to reclamation of worn parts and to protective coatings to resist corrosion.

The Process.

Metallizing can be defined as a process whereby heated metal in a finely divided state is projected onto a receiving surface by means of an air blast. Figure 1 shows metal spraying being carried out for the protection of steelwork, exemplifying its original purpose although the particular application—zinc spraying a steel hull—is a comparatively recent innovation in this country. In order to obtain a balanced conception of the usefulness of the process, Fig. 2 is included to illustrate the reclamation of worn machinery parts—in this case spraying stainless steel on an auxiliary turbo-pump shaft.

FIG. 1—Sandblasting and zinc spraying a steel hull.

FIG. 2—Auxiliary turbo-pump shaft being metallized with stainless steel.

Both classes of work are of interest to marine engineers, but a brief study of the process itself is essential for the intelligent application of either of them.

During its development, metallizing has passed through stages in which first molten metal, then powdered metal and finally wire has been the state in which the material has been fed into the hand tool, known as the metal-spraying gun. The convenience of storage and handling of metal in wire form need scarcely be stressed, although emphasis should be placed on the fact that in the case of wire, the necessity to melt it in order to atomize it implies that every particle must have been adequately heated, whereas with molten metal or powder neither may be deposited with the same guarantee of heat control. Thus, it is not surprising to find that the wire-type of metallizing gun is the one in most general use today. The range of wire metal spraying is limited only by what materials may be obtained in wire form, so that all the common metals and alloys may be sprayed, with the exception of pure chromium.

Figure 3 shows the general arrangement of a typical modern metallizing

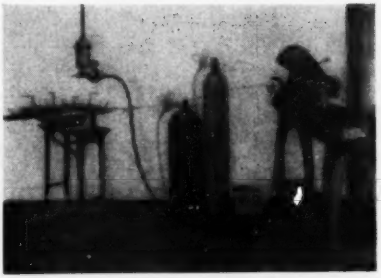


FIG. 3—Arrangement of metallizing gun in lathe showing controls for air, gas, oxygen and wire.

installation with the gun fixed to the toolpost of a lathe. A governor-controlled, high-speed air-turbine through double worm-reduction gearing to a pair of feed-rollers pulls the wire into the gun and pushes it through the central orifice of a close-fitting nozzle. Figure 4 is a diagrammatic representation of the melting and deposition of the wire. A mixture of gas and oxygen is led to the nozzle tip by means of small passages, usually six in number, so as to play small jets of flame on to the wire. Thereafter, an air-stream breaks up the melting wire into small

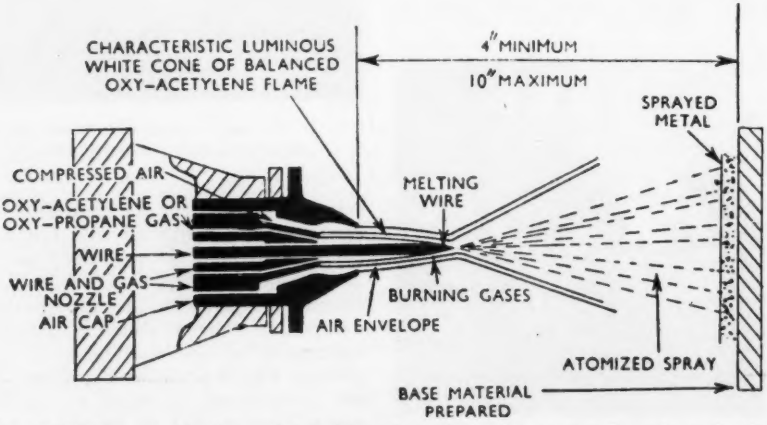


FIG. 4—Melting, atomization and deposition of metal showing section through combustion head of spray gun.

particles, at the same time directing the jet of metal on to the work. The mean temperature of the stream, consisting as it does of a small volume of hot metal and a large volume of cool air, is quite low—so low indeed that it may be directed on to the hand without any considerable discomfort.

An individual particle, once separated from the wire, assumes a roughly spherical shape and is subject to cooling and oxidizing conditions during its flight, which may occupy about one-thousandth of a second. On impact, and according to varying circumstances, the kinetic energy of the particle must largely change to heat, and, thereafter, in most cases it will be in intimate contact with a much larger and cooler body, so that rapid "quenching" results. Coincident with impact, the spherical shape of the somewhat oxidized and externally cooled globule will change to a spheroid, or may even become saucer-shaped. On flattening, the major perimeter will be the part most highly stressed and either cracks or torn, distorted edges will result. Maximum oxidization occurs during the period immediately following impact and continues until covering by subsequent particles has eliminated contact with the air.

From this simple study quite a lot of useful information can be derived as to the nature of sprayed metal. Perhaps the most interesting item is the manner in which the particles are joined together. Mechanical interlocking of the torn edges of particles accounts for much of the tenacity with which they hold together, but this is greatly increased by their tendency to flow on impact so as to key into one another. There is also undoubtedly some form of oxide cementation between particles, and this is probably the major factor in providing tensile strength normal to the surface being sprayed, whereas in a plane parallel to the surface mechanical interlocking provides tensile strength which may be even ten times as great as that normal to the surface. A certain amount of rather haphazard welding does occur between particles here and there in a coating, but is generally of little importance in considering the strength.

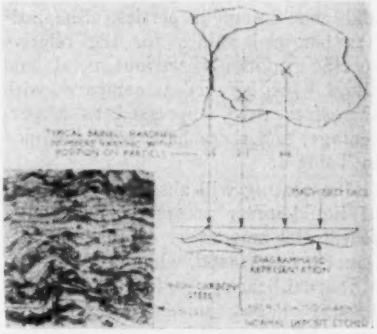


FIG. 5—Variations in apparent hardness due to structure of sprayed metal.

Figure 5 represents diagrammatically several typical particles of sprayed steel, and indicates how misleading an ordinary hardness test can be as shown by readings taken in the center of a particle, nearer the edge, and again at the junction of two particles. The normal difficulties of making due allowance for the coating thickness and the nature of the base material are insignificant compared with the errors arising from the positioning of the test on the particle.

If machining properties are to be considered in relation to hardness, then it is obvious that the properties of the oxides separating the particles must not be overlooked and it must be decided whether the cut will be parallel to the laminations or across them; the "apparent" oxide content being much less in the former than in the latter case, since, although each particle covers a relatively large area, it has very little thickness. Figure 5 includes a microphotograph of sprayed steel which is obviously porous, though not

so much by reason of minute voids as by the oxide layers.

Table 1 tabulates hardness for a range of common metals in the sprayed condition, but is mainly of academic interest, because other factors, such as the porosity and oxide content, have a greater influence over wear-resistance and machining properties. Shepard* has obtained values for the relative specific gravities of various metals and alloys when sprayed as compared with the wires used, expressed as a percentage, and these have been included in Table 1.

The coating will absorb a great deal of liquid under pressure, and even a substantial amount by capillary attraction. Sprayed metal, when used to form a journal-bearing surface, provides a natural oil reservoir, thus eliminating dry-starting conditions with a consequent lessening of wear. It is interesting to note that in the case of crankshafts, records indicate that the performance of sprayed metal compares favorably with the hardest shafts, and that for this purpose there is very little to choose between metallized coatings of soft low-carbon steel or the hardest of high-carbon steels. One cannot avoid concluding that it is the porous nature of sprayed metal that accounts for its excellent properties as a journal-bearing surface. The typical stress-strain curve* shown in Fig. 6 indicates some similarity to a cast material.

Shrinkage of sprayed metal during cooling provides the chief source of stress in a metallized coating, and it varies rather surprisingly as indicated in Table 2. It is obvious that contraction serves to tighten the bond when a periphery is being metallized while the converse is true of internal work on bores, but, in general, shrinkage should be held to the minimum, as it prestresses and weakens a coating, and

*A. P. Shepard, Metco Laboratories, Long Island City, N. Y.

TABLE 1—HARDNESS VALUES AND DECREASED SPECIFIC GRAVITIES AFTER SPRAYING.

Sprayed metal	Hardness, equivalent Brinell No.	Ratio of coating specific gravity to that of wire used, per cent
High carbon chromium steel	296	88.7
80 per cent carbon steel	346	82.5
10 per cent carbon steel	183	86.7
Iron	147	88.4
18/8 Stainless steel	147	88.9
Naval brass	76	89.2

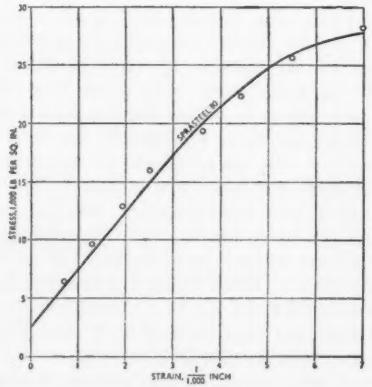


FIG. 6—Typical stress-strain curve for steel.

TABLE 2—INTERNAL STRESSES IN SPRAYED METAL COATINGS ARRANGED IN ORDER OF THEIR RELATIVE ABILITY TO RESIST THEM.

Metal	Skrinkage, per cent	Elongation, per cent at ultimate strength	Ultimate tensile strength, lb. per sq. in.	Remarks
High carbon high chromium stainless steel, No. 2	0.18	0.50	40,000	Internal stresses low; coating strong — the most reliable metals for building-up heavy duty parts
80 per cent carbon steel	0.14	0.42	27,500	
10 per cent carbon steel	0.80	0.30	30,000	High stresses — care must be taken to ensure a good bond
Iron	0.90	0.25	28,000	
18/8 Stainless steel, No. 1	1.20	0.27	30,000	Strong bond essential and slight pre-heating in cold weather to prevent risk of cracking
Naval brass	1.00	0.51	13,000	

may in some cases result in cracking. The permissible amount of shrinkage will depend on several factors, foremost among them being the amount of metal being deposited and the standard of preparation achieved on the receiving surface.

Surface preparation is by far the most important part of metallizing technique since upon its adequacy depends the strength of the bond between the coating and the parent metal. There are numerous methods by which bonding can be achieved, but most of them involve roughening the surface in such a manner that the sprayed metal is mechanically keyed in position by means of suitably shaped depressions in the base material. To produce a strong mechanical bond such surfaces must be rough and free from oil, moisture, etc. As will be seen in Fig. 7 the degree of roughness must be sufficient to allow average-sized particles

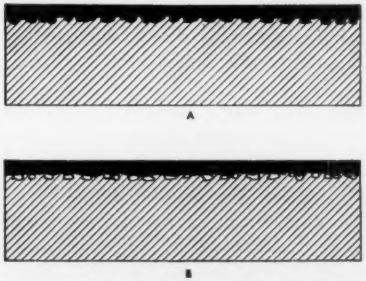


FIG. 7—(A) Character of bond attributable to good blasting preparation. (B) Bridging caused by too fine blasting.

of sprayed metal to enter the depressions without "bridging" them, and the shapes must include a high percentage of undercut depressions in which the deposit can anchor.

A second function of mechanical preparation must not be overlooked. It consists of breaking up the surface so as to expose not only a much in-

creased area of contact, but also to tilt the particles of sprayed metal at widely different angles. It has already been noted that the laminar structure yields much greater strength parallel to the laminations than at right angles to them, and it follows that an irregular surface will distribute this strength more uniformly throughout the coating. While not significant in the case of protective coatings, this factor assumes considerable importance on machine element work and often dictates which method of preparation shall be employed on a particular item. The roughness should, therefore, be of such an order as to "anchor" the coating against contraction stresses, but patterned so as not to produce a change of plane along any given line. A splined shaft is an example of exaggerated roughness without anchorage in some directions and definite weakness along axial lines of maximum stress, where change of shape alters the plane of lamination.

Since various classes of work demand different methods of preparation it is well to understand the several techniques employed and compare their advantages and limitations.

Blasting with Sand or Angular Steel Grit.

Grade 24 abrasive used at about 70 psi. pressure produces on mild steel and other not too hard surfaces irregular depressions which will key sprayed metal. It is by far the cheapest method of surface preparation, but the bond obtained does not permit heavy deposits, being indequate to resist severe contraction stresses. Figure 7 (*A*) represents an enlarged section through a well-blasted surface. The human element enters into sandblasting to such a degree that it cannot be considered reliable, the more so because visual inspection does not easily reveal slightly defective workmanship. It is usual, when employing the blasting process, to rely on rigid control of air pressure and quality of abrasive used and limit inspection to insistence on complete and uniform treatment of all surfaces. Hard cast-iron and heat-treated steels are sometimes blasted with alumina and other extremely hard abrasives, but a similar limitation as to coating thickness still applies.

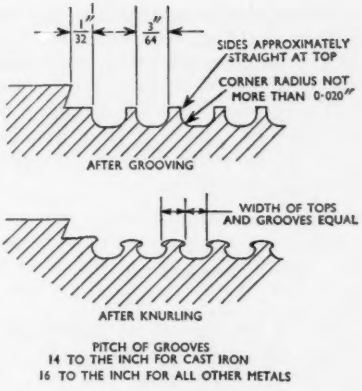
Rough Turning.

This generally produces a bond superior to blasting, although, relying on the small barbs torn up on the surface, it is dependent on the strength of the parent metal, so that in the case of cast iron, brass and similar materials, it is not very useful. A sharp-pointed V-tool ground to about 40° and having little rake or clearance is normally employed to cut from 16 to 24 threads per inch according to the size of workpiece and thickness of coating. Some little skill is required to produce consistent results. Engineers may well look askance at a process involving tearing jagged cuts by way of preparation, but the incidence of failure by fatigue of such work appears to be extremely low, in fact, no instance of such failure has come to the author's notice during the fourteen years he has known the technique to be employed. This may, however, be due largely to the wide margin of safety employed by engine designers, and methods other than rough turning are used by most responsible engineers engaged in the metallizing industry.

The Shaft Preparation Tool Method.

This involves roughening the surface with a special type of knurling tool, using a laminated cutter in which five thin steel blades, each with teeth set at different angles, are rigidly held together. When passed over the surface of a piece revolving in a lathe, a satis-

factory kind of roughening is achieved, which has the advantage that uniform results can be repeatedly obtained. Used alone it is only satisfactory to receive coatings for press fits and other similar work in which the bond is not heavily stressed in tension.


1/32"
3/64"
SIDES APPROXIMATELY STRAIGHT AT TOP
CORNER RADIUS NOT MORE THAN 0·020"
AFTER GROOVING
WIDTH OF TOPS AND GROOVES EQUAL
AFTER KNURLING
PITCH OF GROOVES
14 TO THE INCH FOR CAST IRON
16 TO THE INCH FOR ALL OTHER METALS

The "Metco" Method of Shaft Preparation.

This method, which was invented in the U.S.A. about ten years ago, remains the best method of machine preparation so far devised.

Figure 8 shows diagrammatically how a groove or thread is cut with a round-nosed tool and thereafter the ridges are spread over by using the shaft preparation tool. Although this method can only be employed on machinable materials, it does provide a means of producing uniform and reliable bonds over a wide range of machine element work. The technique is simple, and although two machine operations are involved (compared with one in the case of rough threading), it can be effectively performed by anyone who can use a lathe, whereas, except on mild steel, rough threading to the requisite standard can prove much more difficult than one might imagine.

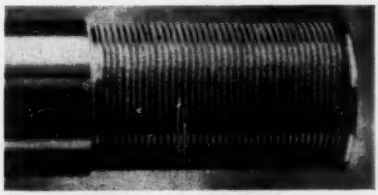


Fig. 8—Preparation of shafting by grooving and knurling.

Fuse Bonding.

Figure 9 is a patented* method of mechanical bonding in which instead of relying only on deformation of the parent metal, as in all previous methods, there is fused to the surface a layer of rough and cratered material on to which the coating metal is subsequently sprayed. Since low-voltage, high-amperage current is required to heat a bunch of electrodes, a transformer,

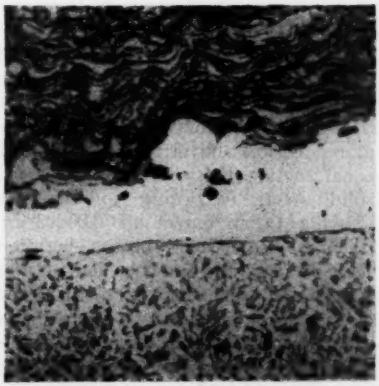


Fig. 9—Fusebond layer between sprayed steel and low carbon steel base.

* British Patents Nos. 575128, 575129 and 575130.

somewhat similar to that used for resistance welding, is employed. The chief advantages are that a good bond can be produced on even the hardest steel parts, and items which cannot be machined by reason of their peculiar shape or excessive size may be prepared for metallizing.

Sprabonding.

This is the subject of patents and patent applications belonging to the Metallizing Engineering Co., Inc., of New York, and has only recently been used here. It appears to be an exceptionally good method of bonding coatings to almost all metals, with the exception of copper and cuprous alloys. It consists of spraying a thin layer (about .0015 to .002 in. in thickness) of a special material onto the base metal, and thereafter applying whatever metal may be required, according to normal metallizing practice. The adhesion between the "Sprabond" and the parent metal is molecular and of the same character as that obtaining between, say, brazing material and steel, or between some metals and the oxides which so tenaciously adhere to them. Figure 10 shows a photomicrograph magnified to 1250 diameters, i.e., it is enlarged 1,500,000 times, so as to show the interface between a steel base and the sprayed layer of Sprabond. It is remarkable in that it indicates molecular adhesion and intimacy of contact equal to that between the crystals of solid steel. According to Ingham† alloying to an extent of 0.00003 in. thickness sometimes occurs between the Sprabond and the base, but no real penetration sufficient to disturb the physical properties of a steel base has been detected. The author's investigations have so far only confirmed that in addition to the adhesion between the Sprabond and base being more than adequate for any known application of the metallizing process, the bond between this special preparatory layer and the superimposed coating is of such a high order that when tested to destruction in tension or sheer, the failure has taken place in the metallizing and not at the bond.

It is, however, necessary to exercise scrupulous cleanliness on surfaces to be Sprabonded, the metal always to be exposed either by grinding, turning or cleaning with emery cloth. Degreasing is not satisfactory, nor is it possible to leave a cleaned part exposed to atmospheric corrosion before Sprabonding. Such care is, however, well repaid by the knowledge that a bond stronger than the sprayed metal itself has been obtained without risk of damage to the base metal.

Fig. 10—Interface between layer of Sprabond and low-carbon steel base magnified to 1250 diameters.

Spray Welding.

This forms a link between metallizing and welding. The material, known as "Metco Sprayweld H" is an extruded plastic in which are embedded certain metals which could not otherwise be made into a wire. Its applications to marine engineering are few but it is mentioned here because it has been

† Chief Engineer, Metallizing Engineering Co., Inc., New York.

successfully employed for the reclamation of Diesel engine gudgeon pins. The material is sprayed on to a surface which has been prepared either by blasting or machining, and is then heated either by oxyacetylene flame, high-frequency current or other means, so as to raise the surface temperature to between 1000 and 1100° C. in order that the deposit may flow and fuse to the base. The resultant coating is extremely hard, being in the region of 550 to 600 Brinell, which is considerably harder than any coating in the as-sprayed condition. Spray-weld deposits, however, do not have the property of oil absorption so that they are generally employed for such purposes as tipping agricultural machinery parts and coating earth-moving machinery blades. Its hardness, absence of porosity and excellent corrosion-resistant properties make spray welding very suitable for certain purposes which demand resistance to both wear and corrosion.

Bonding by Heat Treatment after Spraying.

Use is made of the well-known property of aluminum by which it readily alloys with iron and steel at about 800° C. to protect ferrous metals subject to heat oxidation, by spraying pure aluminum on to a previously blasted surface and thereafter heat treating to produce the heat-resisting iron-aluminum alloy over the surface. Furnace parts are regularly so treated, and the coating becomes integral with the base material. There are numerous other examples of bonds achieved by heat treatment, but they are not important to an understanding of the more generally employed mechanical bonding methods which cover the bulk of metallizing work.

Hand Preparation.

For metallizing this is generally to be avoided, although there are instances in which it can be very useful. One such occasion was during the late war when a destroyer (H.M.S. *Verity*) was found, on trials, to have distorted the port main turbine casing either side of the carbon packing gland, to a depth of about 0.008 in. on each flange. The vessel was required for immediate service, and the author, armed only with a metal spraying gun and some mild steel wire set out to get her to sea with the minimum delay. It was an allnight job to jack up the top-half casing, prepare the low areas on the flanges of both top and bottom halves, and metallize them—the preparation being carried out by making undercut chisel marks in three different directions at about 60° to each other. Admittedly, the deposited mild steel had only to perform "jointing" or "packing" duties, after filing and scraping by the dockyard staff, but it illustrates that hand preparation can be useful. On another wartime occasion severe pitting as much as ⅝ in. deep in places was found aft of the stern glands and forward of the A-bracket bearings on each of H.M.S. *Stevenstone's* propeller shafts. Time did not permit withdrawal of the shafts, and the author had to choose between gritblasting and hand preparation. The latter was selected (except that pneumatic chisels were employed) because the mass of metal required in some areas made it extremely doubtful whether blasting would prove satisfactory. This work was carried out as a temporary emergency repair, but long afterwards the Admiralty confirmed that it was still behaving satisfactorily. Some may wonder how machine finishing of the sprayed metal was carried out on these propeller shafts *in situ* in dry dock. The author claims no part in devising the

method, which was suggested by the shipyard foreman, whereby these shafts were ground very true to a good finish by the simple expedient of cutting a wood block concave to the radius of the shaft and mounting a pneumatic grinder on it with a piece of rubber insertion to allow for pulling up to apply a cut. Figure 11, showing the arrangement used, is included not so much as illustrating a method of finishing sprayed metal, but as a tribute to that ingenuity which is found among marine engineers and shipyard staffs.

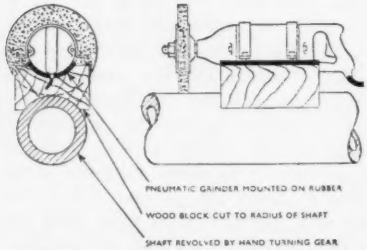


FIG. 11—Improvised grinding arrangements for propeller shaft metallized in situ on H.M.S. *Stevenstone*.

PREHEATING.

This is not often resorted to in connection with preparing parts for metallizing, although a mild preheat is sometimes employed when metallizing internal surfaces such as bores and housings to counteract the effect of coating shrinkage. It must not in any case be carried to such an extent as to oxidize the prepared surface, and can only be used in conjunction with one of the mechanical methods of preparation already described. However, in extremely cold weather, with the workpiece at or below freezing point, it is considered advisable to "take the chill off the job" before preparing, since the surface if very cold rapidly collects moisture, and the mild preheating eliminates unnecessary stressing of the coating and so reduces the risk of low-temperature cracking. Average room temperature of about 60° F. is quite sufficient to obviate this, and the necessity to take any such action will vary with the particular metal being sprayed. As an example, high-carbon steel, which has comparatively high tensile strength, but low "shrinkage value" will not require such precaution in this respect as brass, of which the reverse is true.

Table 3 shows the effects of various types of preparation on the endurance and resistance to both axial and rotary shear stress.

Finishing Sprayed Metal.

Table 4 indicates recommended feeds, speeds, etc., for finishing metallizing work by turning and grinding. Because of its peculiar structure, sprayed metal presents certain finishing problems to an uninstructed operator who has hitherto worked only on "solid" metals.

TURNING.

When a shaft has been metallized on to a machine-prepared surface, it may be found that at each extremity the coating is somewhat harder—in fact, a pronounced hard ring often occurs (Fig. 12). This is due to the flattened

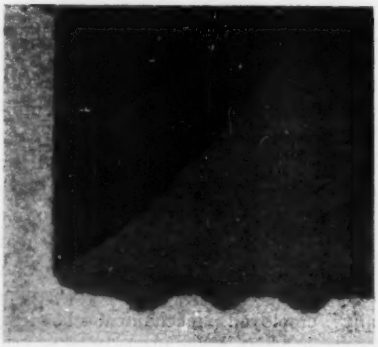


FIG. 12—Example of hard ring found at shoulder.

TABLE 3—EFFECTS OF PREPARATION ON MECHANICAL PROPERTIES (13% CHROMIUM STEEL ON 3½% NICKEL STEEL BASE).*

Type of preparation	Estimated endurance limit, 2×10^7 cycles	Stress concentration factor	Axial shear, lb. per sq. in., 2-inch cylindrical band 0.2 inch wide	Rotary shear, lb. per sq. in., 1-inch diameter × 2 × 5/16 inch × 0.2 helix
Shot blasted with angular steel grit	54,000†	0.76†	1,200	3,150
Rough threaded	30,000	1.37	7,990	14,700
Grooved and knurled (complete "Metco" method)	27,000	1.52	6,000	25,400
Fuse bonded	35,000	1.17	9,000	24,100
Plain polished specimen	41,000	1.00	This specimen not sprayed	

* According to U. S. Bureau of Ships.

† Blasting with sand or steel grit stretches the surface and so prestresses it in a negative sense to those stresses which tend to cause fatigue in service.

TABLE 4—FEEDS AND SPEEDS FOR FINISHING SPRAYED METAL.

Metal	Turning with carbide tipped tool				Dry grinding				Wet grinding		
	Surface speed, ft. per min.		Feed, inch per revolution		Tool post grinder, 5/6,000 surface ft. per min.				Wheels		All metals
	Roughing	Finishing	Roughing	Finishing	Metco wheel	Work speed, surface ft. per min.	Roughing feed per revolution, inch	Finish feed per revolution, inch	Carborundum 6,100 surface ft. per min.	Norton 6,500 surface ft. per min.	
High carbon steel	35	35	0.004	0.003	44	30	1/32	3/64	C36-K4-VE	37C46-K5V	Work speed, 80/90 surface ft. per min.
Low carbon steel	90	90	0.006	0.003	42	30	1/32	3/64	C36-K4-VE	37C46-K5V	Traverse, 3 ft. per min. (roughing)
Brass, bronze, copper	275	275	0.006	0.002	44	30	1/32	3/64	C36-K4-VE	37C46-K5V	Traverse, 1 ft. per min. (finishing)
18/8 stainless steel	110	150	0.006	0.003	43	30	1/32	1/16	A465-J5/6-V30	37C46-K5V	Infeed, none (finishing)
High carbon chrom. steel	35	35	0.004	0.003	46	110	0.006	0.015	C-36-K4-VE	37C46-K5V	Infeed, 0.001 inch (roughing)
Monel metal	225	275	0.004	0.002	46	30	0.006	0.015	GC-60-J8-VW	37C80-H7V	Coolant 45 to 1
Nickel	225	275	0.004	0.002	44	30	0.006	0.015	GC-60-J8-VW	37C80-H7V	

particles of sprayed metal being mounted more or less "on edge" in these areas, since they tend to follow the contour of the shoulder at each end of the prepared section. Such shoulders also collect particles of dust, carbon, etc. It can be minimized by spraying into the corners before proceeding with the main body of the coating. When it does occur, however, it is better to finish-machine the affected areas with a plunge cut rather than axial feed, using a blunt-nosed tool. With most sprayed metals there is a tendency for unskilled operators to tear out particles, resulting in a rough and pitted surface. Bad tearing may even disturb particles which at the time are beneath the surface and so prevent a good finish being obtained at a smaller diameter. It is generally advisable to set the tool a little above the center so that front clearance is practically eliminated and the pressure of the tool immediately below the cutting edge will tend to hold each particle in position so that it will cut rather than tear out. Tungsten-carbide tipped tools should be used for all sprayed metals if possible because they require less rake and clearance than steel tools, and for the hardest materials, a grade which would normally be used for chilled cast iron should be employed.

Dry Grinding.

This generally implies the use of a tool-post grinder, and the recommendations in the table should be closely followed, otherwise glazing the wheel and burning the coating will result. It is important to select the appropriate type of wheel for the particular coating, since selection based on experience of "solid" metals will yield indifferent results in most instances. All metals, when sprayed, lose some of their heat-conducting property by reason of the oxide surrounding each particle, so that they more readily overheat locally, especially when dry grinding is employed. For ferrous metals the Norton 37C46-15V wheel or an equivalent gives very good results.

Wet Grinding.

Wet grinding provides the best possible machine-finish on sprayed metals. Wheels generally are coarser and of lower bond-strength than for normal metals, and if a general-purpose wheel is required, then either of the following vitrified wheels should be satisfactory: Carborundum C36-K4-VE or Norton Chrystolon 37C-46-K5V.

Lapping.

Lapping should never be employed on metallized bearing surfaces, since the abrasive can become lodged in the pores of the metal with serious consequences.

Keyways.

It is better practice to form a keyway during spraying by the insertion of a dummy key rather than to attempt to cut one in an otherwise unbroken periphery of sprayed metal. The latter procedure would release the contraction stresses in the coating and possibly damage the bond. Carbon is very suitable for making up into dummy keys, or for plugging oil holes, etc., while spraying, and presents little difficulty during machine finishing. When fitting a key the coating should be backed away so that the load is carried on the solid metal only.

Machining Allowance.

Allowance is necessary to dispose of the top oxide layer, the natural matt surface of the sprayed coating, and any unevenness resulting from the rough contour of the preparation. As the coating thickness increases, the tendency for initial roughness to follow through decreases, so that the machining allowance becomes less. Generally 0.020 in. measured radially is sufficient when turning and about half that amount for grinding, but it is quite easy to assess what will be required from the character of the work.

Time Lag Between Spraying and Machining.

When working to very accurate limits it is not only necessary to allow the sprayed coating to cool to room temperature, but also to allow it to settle down. Although contraction is a function of temperature the final adjustments in the material do not keep pace with the rate of temperature drop. While this does not affect the normal run of metallizing work, it has been found from time to time that where the metallized coating is considerable in relation to the wall thickness of the parent metal, further action, after normal cooling, can be sufficient to affect dimensions or even distort an accurately ground surface. A recent case, under the author's supervision, involved the metallizing of a large number of cylinder-liners externally. The first few were checked for tolerance (+0.00025 —0.00025 in.) and were well within limits with no ovality. Three days later they were rechecked and found to be oval +0.0005 —0.001 in., with room temperature approximately the same. These liners had shrunk further and distorted after grinding, and it was attributed to the fact that they had been ground as soon as they were cooled. When a time lag of two days was interposed between spraying and grinding, this trouble was eliminated. During the two days following metallizing the "dead" note originally given by a piece of sprayed high-carbon steel changes gradually to a bell-like tone which is suggestive of some internal process continuing beyond the cooling-out stage. The subject is an intriguing one and has been engaging the author's attention for some time, but it is not anticipated that it will lead to any conclusions affecting technique, other than the already recommended time lag in connection with thin shells.

Building Up Machinery Parts.

Building up machinery parts by metallizing covers such a wide range that it is convenient to list a few classes of work connected with marine engineering.

Restoration of Worn Components.

Restoration to plan size is the most commonly undertaken class of work, and the examples are so numerous as to make the selection of a typical case difficult. The selection of a crankshaft (Fig. 13) is done because there have

Fig. 13—Metallizing journals of Diesel-engine crankshaft.

been more crankshafts reconditioned by metallizing than any other single component within the author's knowledge. The total number in Britain alone is probably in the region of 50,000, and although they have mainly been small ones, quite a number of large Diesel crankshafts have been metallized successfully. They provide an excellent example of restoration to original size with elimination of the necessity for undersize bearings and provision for retreatment of the original shaft many times. Some years ago the Admiralty produced an excellent specification for the reclamation of crankshafts by metallizing and this has been the basis for much of the similar commercial work also undertaken in this country. It is not unusual to find that a metallized crankshaft bearing will outlast the standard article, and this is not surprising both on account of the oil-retaining properties of the sprayed metal and because crankshaft materials are often selected on account of their forgeability and toughness, rather than exclusively for wearing properties.

Metallizing Oversize.

To extend the life of a mating part metallizing over-size is frequently resorted to. An example is found in building-up piston and pump rods oversize so that the gland may be bored to suit instead of requiring replacement or rebushing. Quite apart from the economic considerations building up oversize is regularly practiced for such items as piston valves, while shortages of labor and materials often dictate that it shall be employed in cases where standard sizes would normally be used. Pistons for all classes of engines are regularly metallized oversize. Figure 14 shows a rather different type of crankshaft reclamation work in which damage to areas other than journal bearings is being rectified by metallizing.

This Figure shows a crankshaft set up in a horizontal boring machine at the works of Messrs. Vauxhall Motors, Ltd., Luton, being metallized with 77 lb. of high-carbon steel at the ends

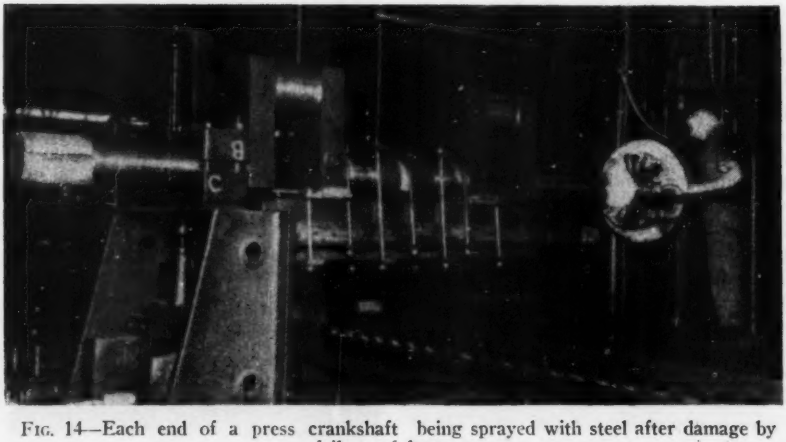


Fig. 14—Each end of a press crankshaft being sprayed with steel after damage by failure of keys.

where the double keys had sheared and torn the surface. The driving gears were bored true but oversize and the shaft built up to suit. Owing to the very great swing involved, no lathe large enough was available and the complete work of machine preparation, spraying and finish-machining was undertaken in the boring machine. For spraying, the shaft with temporary balance weight was chucked at one end while the other end was carried in an improvised pedestal bearing as shown. For preparation and finishing, the job was packed up to the requisite height on to the carrier and the tool held in the chuck. The interesting aspect of this job is that it was undertaken twelve years ago as an emergency repair, with little confidence that it would do more than save an immediate hold-up on production. In fact, it is still operating satisfactorily and illustrates the point that the vast majority of those engineers who have accepted metallizing originally only tolerated it as a temporary expedient and have since been forced by experience to embrace it as sound reclamation practice. Perhaps more important, however, is the fact that in such work as this, the distortion by welding, which was the only practical alternative, would have risked damage beyond repair. In any case it would probably have necessitated machining all bearings true, and no local facilities for remachining the crankpins existed. Considerations such as this form an excellent introduction to a cold process.

Material and labor shortage may often dictate this method of "oversize" reclamation. It is also sometimes employed in instances in which no reduction of "core-strength" of the member to be built up could be permitted. Removal of metal to allow the minimum permissible thickness coating can in this way be eliminated, but even so, it is good practice to ignore any possible added strength due to the deposited metal. In all metallizing reclamation the engineer responsible should decide whether the component is strong enough for service without making any allowance for the strength of the coating.

Metallized Inserts.

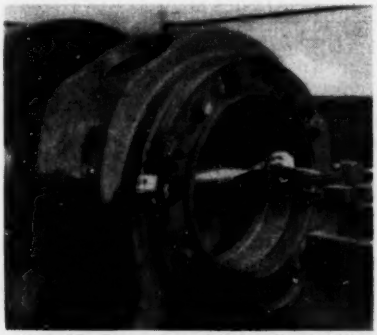


Fig. 15—Pump barrel being lined with sprayed nickel.

These are chiefly employed to permit a more valuable metal to be used only on that part of a component in which its particular properties are required. Both manufacturers and repairers take advantage of metal spraying for this purpose. Figure 15 shows an excellent production application in the practice of G. and J. Weir and Co., Ltd., who line heavy-duty pump barrels with a thick nickel coating. This combines corrosion resistance with excellent wearing properties, whereas it would, of course, be economically impossible to produce the pump barrel completely in nickel, and normal plated deposits would be inadequate to allow for subsequent remachining when worn. Inserts are frequently metallized so as to form sleeves on shafting, and especially mild steel pump spindles which are given a stainless steel or Monel-metal coating on areas subject to corrosion. Circumstances in repair work can sometimes make metallizing the only possi-

ble method of repair, because a sleeve could not be fitted, e.g., a section of a shaft between two collars.

Remedying Machining Errors.

An argument frequently put forward against the wider use of metallizing for this purpose is that once the machine shop people know of its existence, they may become careless in the certain knowledge that mistakes can be rectified. Although this implies confidence in the process, it does so in a negative manner, which might react unfavorably to the wider use of the metallizer. The author has investigated the suggestion in three machine shops and statistics in each case have revealed that the incidence of careless errors has tended to decrease after a spray-gun has been installed for reclamation. It is believed that this is largely due to the fact that metal spraying a machining defect gives much greater publicity to the error than does the making of a new part. At any rate, some hundreds of machine shops, in Great Britain alone, include a metallizing gun in their equipment, using it as a "putting-on tool" with the same confidence that they show in employing an orthodox lathe tool. The classes of work include not only shafting, but bores and internal ballrace housings and flat surfaces. It is not usual to build up screw threads by metal spraying, since, in general, the shear stress on the bond is too great and in any case sprayed metal is not very suitable for this class of loading owing to its structure. Much the same may be said of the actual working faces of ball and roller races, in which the respective point and line contacts impose too great a stress trying to force the particles of sprayed metal apart. It is true that some ball and roller races have been successfully built up by metallizing, but only in cases of very light loading, with the exception of work recently carried out by the spray weld process.

The suitability of spray welding to carry heavy localized loading is due both to its hardness and to the fact that the heat treatment results in the sprayed particles flowing together so that the coating can no longer be regarded as a regular sprayed-metal deposit. For press fits and shrunk-on collars, sprayed metal, particularly if loaded with oil or colloidal-graphite, exhibits considerable resistance to "fretting-corrosion," that is to say the type of corrosion which is believed to result from the slight relative movement of two parts, one of which is subject to severe alternating stresses only partially passed on to the second member by virtue of the tightness of the fit. A gear wheel shrunk on to a crankshaft is an example. Sprayed metal itself, when forming a sleeve on a shaft—a crankshaft again being an excellent example—might well be expected to exhibit this phenomenon, but it has only been found on one occasion by the author, and the part was a thick coating on the nonlubricated end of a large industrial crankshaft, which was being examined after many years service (it had been prepared by blasting before any of the later surface-preparation techniques had been devised), and was comparable with what might be expected of a shrunk-on sleeve.

It is believed that by any of the other methods of mechanical bonding outlined in this paper, the keying effect is sufficient to prevent relative movement, even the microscopically small movement that can give rise to this form of corrosion, so that such vibrations and stresses as occur in the parent member are passed on to the coating. This matter is not merely of academic interest, since fretting or rubbing-corrosion can be a factor in giving rise to such stress concentrations as may ultimately cause failure by fatigue. While there remains room for much more useful work to be done on this aspect of coating parts subject to alternating stresses, it is

encouraging to note that all the evidence of metallizing work during the past fourteen years appears to indicate that the process combats fatigue rather than encouraging it. Referring to Table 3 comparing bond strengths it is worthy of note that blasting stretches a surface in such a manner as to render it less liable to fatigue than a similar polished surface, and this even though a sharp abrasive be employed.

Oil Absorbent Bushes.

These may be formed either by lining conventional bushes internally by spraying or may be manufactured entirely by metallizing. Babbitt metal is generally employed as the actual bearing metal and the method of manufacture of of complete bushes by metal spraying is as follows. A very slightly tapered and undersized mandrel is cleaned and "dulled," but not roughened, by blasting. Babbitt metal is then sprayed over the mandrel to the requisite thickness, usually 12 to 15/1000 in. but with the thickness compensated for the mandrel taper so as to finish parallel. Thereafter, the spraying is continued to give a wall thickness of from ⅛ to ¼ in. with whatever metal may be required for the bearing shell, steel, bronze, aluminum and even magnesium having been employed for this purpose successfully. Thereafter, the outer surface is turned to finished dimensions and the bushes parted off, it only remaining necessary to reamer the bores parallel (located by the perimeter) to complete the machining. Before putting such bushes into service they are impregnated with oil containing colloidal graphite by dipping, or, if maximum absorption is required, by subjecting to a vacuum followed by oil under pressure. Bushes of this kind are economical to manufacture and are particularly suitable for inclusion at points where lubrication may be neglected by reason of inaccessibility.

Casting Faults.

These are not always detected before it is too late to replace or uneconomic by reason of considerable machining work having been carried out. The informed engineers will in such cases wish to consider whether the defect can be remedied by metal spraying, but will have well in mind that metallizing does not substantially strengthen a casting. Having decided that the part has the requisite strength he will know that metallizing can be employed for the following purposes:

(*a*) Building Up Where Undersize: Provided that the bond between the coating and the casting is not subject to considerable shear-stress, nor the resulting surface liable to impact or excessive localized loading the process is as previously described.

(*b*) Sealing Porosity in Castings: This may at first sight seem contradictory in relation to the claims made for the oil absorbing properties of sprayed metal, but not so when it is realized that the porosity of the coating is a function of the thickness. The paths through sprayed metal become increasingly devious as the thickness increases. Furthermore, by decreasing the distance of the gun from the work, the incidence of welding between particles increases—and slight preheating of the casting (insufficient to cause oxidation) can be used to exaggerate this until porosity is eliminated.

(*c*) Cracks in Castings: These can often be temporarily, and in some cases permanently, prevented from leaking even under considerable pressure. The technique of repairing cracks, except in cuprous alloys, has been greatly improved by the invention of Srabonding.

(*d*) Unsightly Blowholes: These can be sprayed with metal matching the casting, and when occurring on a working surface can, by careful selection of a material giving an equivalent wear-resistance, be made to render an otherwise useless part quite serviceable.

Metallizing Patterns.

Perhaps the chief use of metal spraying in connection with patterns in ship repair work has been to apply quickly the necessary machining and shrinkage allowances on actual castings which have to serve as emergency patterns. The parts requiring added metal are cleaned, preferably by blasting, but sometimes only by rough filing, and a coating of zinc applied to the necessary thickness. This is particularly convenient on parts which, owing to their shape, cannot readily be enlarged for use as a pattern by the usual means. Additionally, patterns for repetition work can be made undersize of wood and then metallized, with the advantages of lightness in use, easy alteration by spraying metal to thicken a webb or alter a curve, and elimination of warping.

Emergency Repairs.

Ship repair work is so frequently a matter of urgency that many of the classes of work already mentioned fall within this category at some time or other. The work on the port main turbine casing of H.M.S. *Verity*, described earlier, is an example, and another instance occurred on the same vessel which illustrates how well metallizing is adapted to eliminate delays in shipping. Figure 16 shows the top and bottom halves of *Verity's* port circulating pump, damaged by an underwater explosion at the same time as the other major defect. The pump, originally manufactured in France, had no patterns or spare parts available and was so distorted that the author could get his fingers between top and bottom casting flanges. The bearing housings were pushed upward 5/16 in. and the impeller-boss axial clearance increased by $\frac{5}{8}$ in. Time was the essence of the repair, and metallizing solved the problem. A 140-lb. weight of bronze was deposited over the "low" surfaces, and the two castings remachined to original dimensions with completely satisfactory results.

The chief factors favoring metallizing for emergency repairs are:

1. Speed with which the work can be carried out—as much as 20 lb. of steel or much larger quantities of lower melting point metals can be deposited in an hour, so that it is quicker than welding to apply, and much less machining allowance is necessary by spraying.

Fig. 16—Top and bottom half castings of a circulating pump built up with 140 lb. of bronze on flanges, bearing housings, etc.

2. Risk of heat damage is eliminated so that parts can often be metallized *in situ*, e.g., a turbine bearing can be metallized with the rotor in position without fear of distortion, and the same applies to sealing a crack in a Diesel engine cylinder block water jacket. Figure 17, showing the metallizing of a turbine shaft *in situ*, is typical. Figure 18 formed the subject of an *in situ* repair on an ammonia compressor and, although similar to marine engineering applications, this work was carried out in a London brewery under the guidance of the chief engineer. The gland cover was removed so as to expose the shaft which was metallized

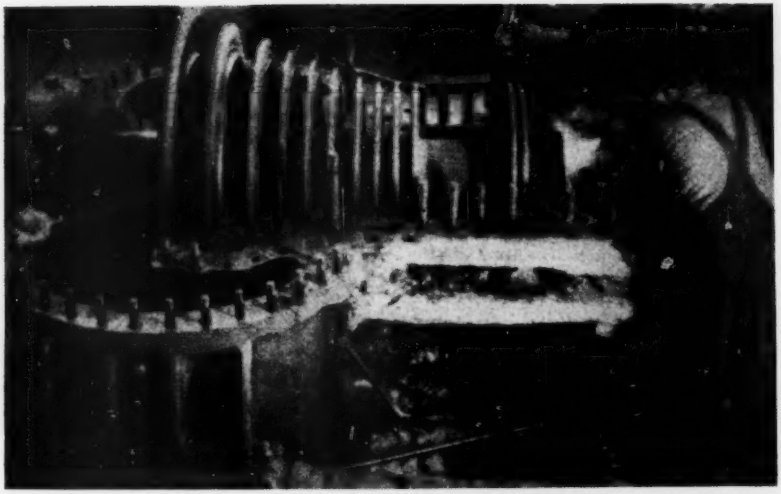


FIG. 17—Turbine shaft being repaired in situ.

with stainless steel and reground with a portable tool post grinder successfully without removing the shaft from the compressor.

3. The most appropriate metal can be selected without reference to its fusibility to the parent metal, so that a limited variety of metal wires will cover all likely classes of repair work.

4. It permits using worn and oversize mating members with consequent advantage.

5. Metallizing is often the only possible means of salvaging a worn part, and yet it involves no special plant with the exception of the hand gun provided an adequate supply of compressed air is available on site.

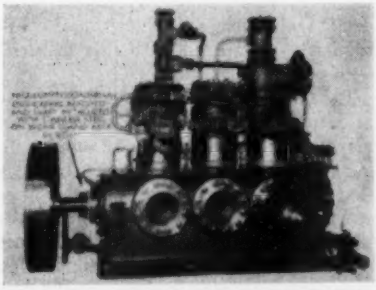


FIG. 18—Ammonia compressor repaired without dismantling.

GENERAL MARINE APPLICATIONS OF BUILDING-UP WORK.

The ideal example of metallizing, and one which is not only well proved, but particularly easy to accomplish, is building up an unbroken periphery, such as a journal bearing. Whereas it takes approximately three days for an operator to be intensively trained in all classes of building-up work (provided he is able to use a lathe), in a single day a man of average intelligence will be quite capable of learning how to build up worn journal bearings faultlessly. The manufacturers of metallizing equipment train operators, although with such a book as the *Metco Metallizing Manual* in his hands, a foreman can quite easily train a machinist in preparation, spraying and finishing, beginning with the straightforward reclamation of bearings.

Propeller shafts are perhaps the simplest class of work on which to begin, and are well worth doing, not only on account of the longer service obtainable from metallized journals, but because such shafts do not readily lend themselves to welding on account of distortion. Steel or bronze shafts, large or small, at the A-bracket bearing, stern gland or any plummer block bearings, are all equally suitable. Figure 19 shows two guns simultaneously spraying a propeller shaft journal.

FIG. 19—Propeller shaft journal being metallized in a lathe.

The period just prior to D-Day found metallizers busy around the southern coast of England making good the ravages of corrosion on the tail shafts of landing craft. With salt water as the electrolyte and steel shafts against bronze bearings, many of these craft had stood in creeks and rivers long enough to "rust-up solid," and but for the metal spraying process might have presented a major problem. Fortunately, it was found possible to salvage these shafts well inside the time limit.

The turbo-pump shaft, illustrated in Fig. 2, is typical of repairs to auxiliary machinery, which, of course, include also all types of pump and piston rods. Where corrosive conditions are encountered, stainless steel and pure nickel are the general choice, and as a rule stainless steel is favored for a rotary part and nickel when reciprocating motion is involved. Stainless steel is not recommended where it would be in contact with leather packing; it is, however, one of the metals chiefly employed on shipwork, so that a word as to its properties in relation to the solid metal may be worthy of inclusion here. In order to retain its quality of resistance to corrosion, stainless steel must have a high finish, such as is imparted by grinding. The characteristic matt finish in the sprayed condition is, therefore, not the most suitable type of surface to withstand corrosion and must be corrected by turning or grinding. It is worthy of note that the time taken to heat, atomize, deposit and cool the metal below the critical temperature during spraying is insufficient to permit migration of carbon to the grain boundaries, so that, unlike welding, there is no risk of "weld decay" when spraying any of the wide range of austenitic steels. A material developed from the well-known 18-8 stainless steels is often employed where corrosion resistance is all important. High-chromium steel known as "Metcoloy 2" is by far the widest used metal for building up worn parts which, in addition to requiring reasonable resistance to corrosion, must be particularly hard wearing. Pump rods, hydraulic rams, deck and dock machinery parts are regularly metallized with this material with excellent results.

Pistons have recently received more attention from a metallizing point of view due to shortage of supply. In general it was considered previously that only really large pistons were worthy of treatment, except that the skirts of small pistons were sometimes metallized to take up piston slap. Ring grooves are not usually metallized, since as new rings are usually called

for it is easier and cheaper to make the new rings wider than the original and machine the grooves oversize. The lands between the grooves on the larger pistons are now regularly sprayed, a shoulder being left at each end of the land when carrying out machine preparation.

Some experiments with the reclamation of aluminum and light-alloy pistons are not without interest. These can be built up with high-carbon steel with only negligible increase of inertia forces, and have very good wearing properties. Tests suggest less cylinder or liner wear than when the "solid" aluminum or light alloy pistons are employed. Metallizing has also been employed to rectify piston top damage, and within pistons, bands of copper have been sprayed to conduct heat away from undesirable hot spots.

The more difficult problems connected with building up by metallizing relate to the treatment of flat surfaces or spraying internally in bores. In general these classes of work require more particular attention to preparation so as to anchor sufficiently well to take care of contraction stresses. Wherever possible spraying of flat surfaces is continued over edges, and if a heavy coating is required it is advisable to Sprabond the surface before applying the coating material. Internal work, of 3½ in. diameter and above, can generally be carried out satisfactorily, but where spraying is all from one end of a small bore, then unless extension equipment is used in connection with the gun, it is not practical to spray the bore to a depth greater than the diameter, or twice the diameter, if spraying can be carried out from each end. The reason is that the spray should strike as nearly as possible normal to the surface, but in no case at an angle of less than 45°. Where greater depths are required, the front of the metallizer is extended by a tube, and a deflecting nozzle, known as an angular air cap is employed to deflect the spray sideways on to the walls of the bore being treated.

Figure 20 illustrates internal work—a recent instance of remedying clearance between the stern-tube and bore of the stern-post on a Gosport-Portsea ferry steamer. The 9-in. diameter hole was Sprabonded and metallized with 15/1000 in. thickness of zinc, scraped true and the stern-tube pressed back in place in less time than would have been required for fitting "shims" and the result was much more reliable.

FIG. 20—Repair of oversize bore in sternpost.

Protective Coatings.

THE THEORY OF CORROSION.

In order to be in a position to select a suitable material to resist particular conditions of corrosion, it is necessary to have at least an elementary conception of the theory of corrosion, and in addition to understand the structure of sprayed metals so that due allowance can be made for its influence upon the problem. So many factors affect the rate of corrosion between metals—and some of these factors are so elusive—that it is good practice to confine actual work to classes for which there are successful precedents or, alternatively, to carry out tests under circumstances which as nearly as possible duplicate the conditions of service. Only by such means will the marine

engineer be able to apply corrosion resistant coatings with confidence, and even then if his opinion is based on laboratory tests rather than actual experience, results may not justify expectations. Fortunately, however, we now have a wealth of experience on which to draw, so that reference to the theory of corrosion is made mainly as a matter of interest though it can be useful in the selection of likely metals for a test. Corrosion problems in connection with metal-sprayed coatings commonly involve two metals only, so that it is worth while considering the effect that one metal may have on another. It is possible to arrange metals in order, based on their tendency to set up galvanic corrosion on each other. (This is not quite the same thing as the electro-chemical series, though similar.) The list begins with materials which are the more readily attacked, or what is known as the anodic end of the series, and continues in order of merit until it ends in the more noble or cathodic materials which themselves derive protection from contact with the more corrodible metals higher in the last.

The metals are grouped and those in each group do not possess any strong tendency to set up galvanic corrosion with each other. Contact between metals far apart in the list tends to corrode the one in the higher group. Circumstances may cause metals to change their position in this list, but usually only within a group, i.e., not between groups. The chromium-irons and chromium-nickel-irons, however, are an exception in that they take one or other of the positions indicated according to oxidizing conditions, acidity and chloride in solution. The list as arranged, however, is correct for a large number of dilute water solutions including sea water and both weak acids and alkalis.

GALVANIC SERIES*.

Corroded end (anodic):
Magnesium
Aluminum
Duralumin
Zinc
Cadmium

Iron
Chromium iron (active)
Chromium-nickel-iron (active)

Soft solder
Tin
Lead

Nickel

Brasses
Bronzes
Nickel-copper alloys
Copper

Chromium-iron (passive)
Chromium-nickel-iron (passive)

Silver solder

Silver
Gold
Protected end (cathodic)
Platinum

---

*From "The Corrosion Resistance of Metals and Alloys," by McKay and Worthington.

Sacrificial Action of Anodic Coatings. All marine engineers are familiar with the protection afforded to steel by the introduction of zinc slabs in intimate contact with the steel, and as near as possible to any corroding influence. The degree of protection varies inversely with the distance from the zinc slab, so that if the steel could be covered all over with a large number of very small zinc slabs, it might be anticipated that whereas the zinc itself would be attacked, complete protection would be afforded the steel. This, in fact, is just what happens when steelwork is zinc sprayed on all exposed

surfaces. The commonest material requiring protection by metal spraying is, of course, steel, denoted in the galvanic series by its main element, iron. Anodic protection of steel is afforded only by those metals appearing higher on the list, and aluminum, zinc and cadmium are all employed for this purpose, although cadmium to a much lesser extent on account of its high cost. It may at first sight appear absurd to use a metal which will corrode in order to protect another metal. The explanation is that while the initial attack on exposed zinc or aluminum will be rapid, the oxides which form during the attack stifle further action until they themselves are either mechanically removed or dissolved so as to expose more of the protecting metal. Protection may thus be truly described as being afforded by the zinc or aluminum oxide, respectively, the balance of metal remaining in the coating acting rather as a reservoir to supply further oxides to replace losses. It is unfortunate that rust—the oxide of the commonest metal, iron—has no such advantages, but it is an easy matter to replace it with a surface which will behave in the manner described.

It has already been noted that sprayed metal is porous, but this provides no great difficulty when using the coatings to give anodic protection because the formation of the zinc or aluminum oxide seals the pores and prevents exposure of the steel base. While aluminum may claim certain advantages, especially in industrial atmospheres, because its oxide is not so readily soluble in rain water, zinc is the metal recommended for protection of steel against sea water corrosion both for immersion and for very salt atmospheres. For immersion in hot fresh water—particularly hard water—aluminum is the better coating, although it gives disappointing results with some soft waters. Zinc, however, is not satisfactory in any water at temperatures exceeding 125° F.

Anodic coatings fulfill two useful functions in service, after initial attack has occured; they protect a surface mechanically (as indeed most coatings do), and in addition sacrifice themselves in such a manner as to continue to give protection. Even if damaged, as by scratching, the oxide tends to bridge any gaps, and if too great to be bridged the very presence of the anodic metal in close proximity and intimate contact will retard the corrosion rate of the exposed surface.

Cathodic Coatings. Cathodic coatings are sometimes employed for protecting parts from corrosion. Because the average engineer has a working knowledge of how metals behave in the "solid" state, he is apt to expect too much of cathodic metals when sprayed. This is largely due to the porous nature of sprayed metal and unless considerable thicknesses of cathodic metals are employed, coatings fail by reason of attack on the parent metal through the pores of the sprayed coating. Reverting again to the galvanic series, it will be noted that there is an extensive list of metals below iron which are all cathodic to iron—some indeed, such as copper, are pronouncedly so. Consider, therefore, what happens when a thin coating of copper is sprayed on iron or steel. The electrolyte, which may be rain water, sea water or perhaps something more corrosive, will find paths through the copper by which it can attack the steel. Since the steel is anodic to copper, the copper will tend to be protected by its contact with the steel, and the steel itself may be the more rapidly attacked. The sacrificial action so laudable in zinc or aluminum with respect to steel is the source of weakness when the steel becomes the anode and is itself sacrificed. Cathodic coatings if too thin and porous, or having pinholes, scratches or other means of exposing the anodic base material, may accelerate corrosion rather than retard it. Once this basic principle is properly under-

stood, it follows naturally that cathodic coatings such as stainless steel, tin, lead, nickel, bronze, etc., must be rendered impervious to the corroding influence either by the thickness of the coating employed when applied to machine element reclamation work, or by sealing the porosity in thinner coatings—a course frequently resorted to when applying coatings to resist corrosion.

Sprayed tin, which is quite an expensive metal, requires approximately 15/1000 in. thickness to prevent access by most liquids, and even then must be scratch-brushed with a stiff wire brush to close mechanically the pores as far as possible. With liquids of low viscosity even thicker coatings are necessary. However, even half this amount can be used satisfactorily if the pores are originally sealed by spraying, brushing or dipping with a suitable sealing medium to withstand the particular conditions of service. A type of bakelite varnish is sometimes employed for this purpose, while on other occasions chlorinated rubber may prove more suitable. Sprayed lead is often similarly sealed. It is less usual to seal nickel, copper and their alloys, as these are largely restricted to building up worn parts where the coating thickness will be sufficient to prevent contact between the base metal and the electrolyte but where excessive pressures are anticipated, as with hydraulic rams, linseed oil mixed with 5% by volume of cobalt liquid drier is found suitable.

Coating Thickness. It will be obvious from the foregoing that a great deal depends upon the thickness of coating employed and the total life of anodic coatings is very largely proportional to their thickness. Aluminum and zinc are generally applied in thicknesses varying from 0.004 to 0.012 in. according to the conditions of service and life required. With cathodic coatings the thickness is more critical in that below a certain minimum, which will vary according to circumstances, such coatings are useless by reason of their porosity while above that minimum, except for a reasonable margin of safety and allowance for mechanical loss by abrasion, if any, additional life may not be achieved by increasing the thickness. Before using cathodic metals for coating work, therefore, one is well advised to consult suppliers of equipment for their recommendations until sufficient experience has been gained within one's own particular field. The measurement of thicknesses of non-magnetic coatings on to magnetic bases and, of course, more particularly the commoner coatings of zinc and aluminum, are generally determined by either an electric layer thickness meter or a magnetic meter which respectively interpret electrostatic capacity of a small area of the plate or, similarly, the interference of the magnetic field from a small permanent magnet, so as to give the mean thickness of the part of the coating being tested in thousandths of an inch. However, most commercial work is carried out very uniformly to the requisite thickness by weighing an amount of wire for a given area until the operator has sufficient practice in applying coatings to know when he has deposited the requisite amount. Uniformity of thickness is achieved much more easily than might be anticipated. The ribbon of metal deposited in a single pass of the spray gun tends to be thicker toward the center than at the extremities, so that parallel strokes should be applied, each successive ribbon overlapping the previous one by approximately one-third. With modern equipment it is usual to arrange the speed of movement of the operator to coincide with a deposition of 0.002 in. thickness for each pass, and for subsequent layers to be applied by making passes at different angles. Where two coatings of 0.002 in. each are to be applied, the second is applied in a direction at right angles

to the first. If three coatings are used it is convenient to make the angle 60° between each coating. It follows that the greater the number of coats applied, the more nearly will uniformity be achieved. For flat surfaces ¼-lb. zinc or 1⅛-oz. aluminum will produce a coating of 0.005 in. thickness and pro rata. On narrow sections and on edges due allowance must be made for losses, but in practice it all becomes much easier than its description may imply. If measurement of thickness is read by a micrometer, then additional allowance must be made for the characteristic matt finish, so that the average thickness is somewhat less than the apparent thickness read by such means.

Finishes Applied Subsequent to Spraying.

Painting. The matt surface of sprayed metal renders it very suitable for bonding paint and, unlike galvanizing, no "weathering" is called for since no acids have been employed in producing the coating. The success of the painting will largely depend on the choice of paint, which must be suitable for the matt surface and selected as appropriate to the particular metal of the coating. The former consideration applies to all sprayed metal coatings and, in general, it is important that the paint must not be so thin that it will be absorbed in the pores of the sprayed metal or so thick that it will bridge across the "valleys" in the matt surface. Quick-drying paints should be avoided, except when a very thin coating is to be employed, e.g., a lacquer finish for appearance. When paint is to be applied to sprayed zinc it is recommended that zinc chromate or iron oxide-zinc chromate paint be used, and these should preferably be in long oil varnish vehicles or those made with bakelite and glycerol-phthalate resins. Bituminous base paints are sometimes used but are not generally regarded as being equally satisfactory. Red lead must not be used with zinc coatings nor must anti-fouling compounds be employed with them since most of these contain metallic copper which would result in rapid corrosion. Paints which are suitable for use on zinc coatings are generally suitable for aluminum, and in addition pigments such as aluminum, iron oxide, red lead, titanium oxide and zinc oxide held in durable vehicles may be used on top of sprayed aluminum.

Coatings Used to Support a Sealing Medium. Reference has already been made to sealing metal-sprayed coatings, but there is another aspect of this which involves the use of the sprayed metal largely as a vehicle to hold a second material. It has been found, for instance, that protection of tanks to hold certain edible oils is afforded just as much by an extremely thin coating of, say 2/1000 in. thickness of aluminum as by a coating many times thicker, but only if, immediately after spraying, the coating is saturated with the particular oil which it is intended to carry in the tank. The sprayed metal holds the oil in its pores by capillary action so that even when the tank is emptied a layer of oil will be interposed between the atmosphere and the mild steel tank, so preventing corrosion. Another somewhat similar example is the use of a very thin coating of zinc or aluminum, followed by brushing, spraying or dipping with a solution of zinc chromate. The zinc chromate held in the pores inhibits corrosion so long as it remains present.

Steel Hulls.

Reverting to Fig. 1 showing the zinc spraying of a ship's hull this work proved unsatisfactory. Because the vessel's bottom had previously shown only negligible corrosion it was not zinc coated. Thus the only wetted zinc was

a narrow band in the region of the water line, forming a relatively small anode with metallic and liquid paths to the large cathode formed by the steel bottom. Rapid attack on the ship's sides first destroyed the paint and then consumed the zinc, though the comparatively dry zinc coating on decks and superstructure was scarcely damaged. Thus, failure to appreciate the factors governing corrosion made it necessary to respray the sides and eventually to metallize the ship's bottom although it had previously not been thought necessary. Some of the details already discussed can now be applied to this important application of the process. The recommended procedure is as follows:

1. Where small vessels are concerned considerable advantage may be derived from carrying out the work under cover when possible because otherwise weather conditions can cause delay.

2. It is necessary to rig up staging for the work and the author has found it well worth while rigging tubular scaffolding so as to eliminate delays in moving from one part of the hull to another. This is particularly advantageous in that it permits blasting to be carried out in one area and then continued in a second area some distance away while metal spraying can be carried out immediately after each section has been blasted without holding up further blasting work.

3. Tarpaulins are arranged around the scaffolding so as to form cubicles to minimize risk from the flying abrasive.

4. A sharp angular flint grit or other sharp sand of between 12 and 20 grade is employed. Steel grit would be quite effective, but there is usually so much loss of abrasive on this class of work that it is much cheaper to employ a suitable sand. Sea sand is smooth and unsuitable.

5. Each part of the work to be treated is blasted to a rough and silvery finish, and if existing rust is very considerable it may prove economical to carry out preliminary chipping, or in some cases flame cleaning, though the latter is not usually necessary, and in any case only in certain comparatively small localized areas.

6. Zinc is used for ship's hulls because it is superior to aluminum for immersion in sea water. It is recommended that a hull be metallized all over since leaving part untreated may call for too much "sacrifice" by the zinc. In any case all the immersed surface must be treated.

7. The spraying of each section must be carried out immediately after blasting. It is not satisfactory to leave an area in the blasted condition overnight. The spraying should keep time with the blasting. The speed of blasting is dependent on the volume of compressed air available. Modern metal spraying equipment, which can deposit up to 55 lb. zinc per hour permits metallizing at a rate exceeding the highest blasting rate.

8. Where an area must be left for an hour or two zinc should first be applied lightly over the whole surface to be left and the work completed as soon as possible thereafter. Even a thin zinc coat will prevent early damage to blasted surfaces, otherwise the blasting should be carried out a second time.

9. The recommended thickness of zinc for steel hulls is 10/1000 in. and this represents the use of ½-lb. zinc wire per square foot.

10. Vessels having steel propeller shafts and cast-iron propellers may have the exposed part of the shaft and the propeller coated with zinc similar to the treatment of the hull, but vessels fitted with bronze propellers and shafts must have such parts coated with Monel metal. The thickness of

Monel metal on the bronze shaft and propeller should be 12 to 15/1000 in. when finished. If the propeller shafts are drawn for this purpose then the spraying of the shafts can conveniently be carried out in a lathe and they can be finished-machined so as to form a sleeve of Monel metal similar to the building-up work described earlier. If this is not possible, then the preparation of the shafts and of the propellers needs much greater care than is the case with the work on the ship's hull; very considerable roughness of the base material being required to make a satisfactory bond for the Monel metal. These remarks apply particularly to the edges of propeller blades, and it is safer to employ either Sprabonding or fuse bonding on the shaft and propeller unless a very high standard of blasting can be achieved.

11. The subsequent treatment of the hull is, of course, as described in the section dealing with painting of zinc coatings, particular reference being made to the remarks concerning the use of antifouling compounds. Sprayed zinc itself has some antifouling properties in cold waters.

12. Generally it should be observed that the life of the zinc coating is very largely proportional to its thickness, so that areas of maximum attack as, for instance, the "wind-and-water" area just above water level may have a slightly thicker zinc coating, or any other part of the vessel where corrosion is found to be particularly rapid. In the same way it is possible to economize somewhat on areas which experience has proved to be less rapidly attacked.

The zinc spraying of steel hulls has been carried out much more in America and certain European countries — notably Sweden—than in Great Britain, although much has been done here during the postwar period. Figure 21 shows an American fishing vessel being zinc sprayed for protection. One prewar example of sprayed zinc on a vessel impressed the author very favorably. A dredger had part of its deck metal sprayed where the action of salt water, plus abrasion by ballast falling on the decks during unloading, had very much thinned the deck plates until there was definite danger of failure. The vessel discharged ballast nightly, polishing part of the deck in so doing. The following day on putting to sea to refill with ballast the deck rapidly rusted, so that the cycle of rusting and polishing was in operation daily. It was considered at the time that zinc might not sufficiently well resist abrasion, but the comparison was not between zinc and steel, but between zinc and rust. The zinc spray was regarded as highly experimental, but it performed better than had been hoped and is still giving good service. A difficulty was encountered recently when one of a number of barges that were zinc sprayed rapidly threw off the subsequent coating of paint. It was found that the paint had been applied while the sprayed zinc surface was covered with frost, and, of course, as might have been expected, this interposed layer completely destroyed all chances of a good bond between the paint and the zinc. But this happens when paint is applied to frosted steel plates also.

Some partial failure of zinc-sprayed hulls occurred before the necessity to coat the bronze propellers and shafts with Monel metal was fully appreciated. Zinc coating the bronze parts is not a reliable alternative, since mechanical damage to the coating—a thing always likely to occur with a propeller—rapidly results in coating failure, though zinc, sealed with chlorinated rubber, has been used with some success. Similar damage to a steel hull, or indeed to a cast-iron propeller, does not have the same dire results. When the various points already made are appreciated by those in charge of metallizing a ship's hull, the process proves not only reliable but of lasting

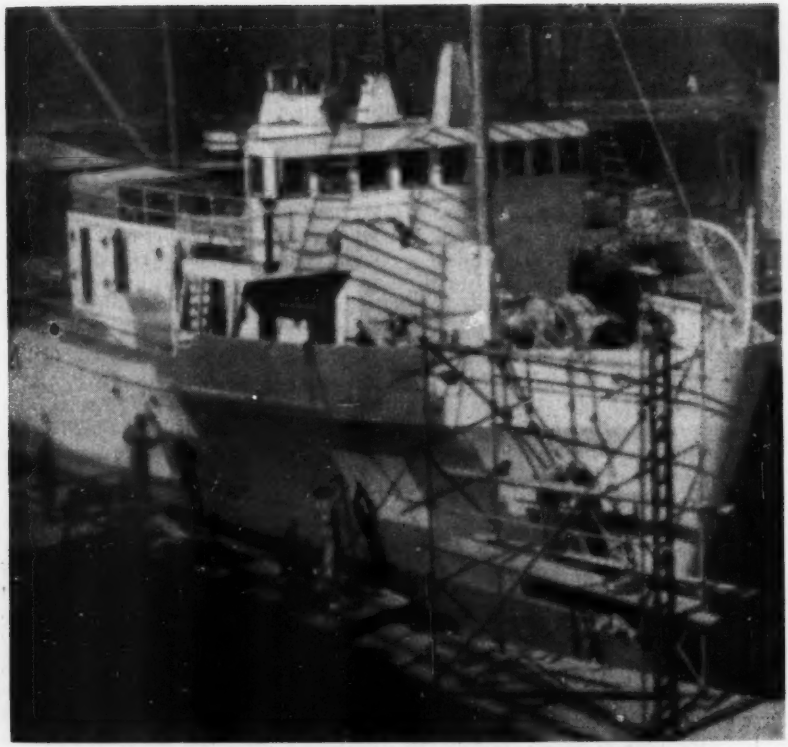


FIG. 21—American fishing vessel afloat being zinc sprayed from pontoons.

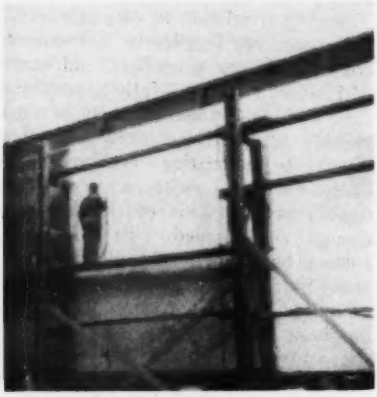


FIG. 22—Early example of steel hull being sprayed with zinc.

value. Figure 22 shows a large American coal barge being metallized in 1934 and the most recent reports indicated that it was still giving excellent service.

PROTECTION OF MISCELLANEOUS PARTS.

Steel tanks and holds are regularly metal sprayed. There is, however, no complete answer to such a combination as oil fuel on one trip followed by salt water ballast on the next. Where tanks are employed for one specific purpose, metal spraying usually gives adequate protection. Deck fittings are regularly treated. It is interesting to note that aluminum fittings for yachts, etc.,

have been given added life by spraying with high-purity aluminum, the oxidized surface so produced imparting some immunity from salt water attack. Furnace parts such as air cones for oil-fired boilers, and fire bars in coal-burning boilers have been protected against heat corrosion by spraying with high purity aluminum. Refrigeration rooms, including coils and fittings, are often zinc sprayed to prevent corrosion. The list, of course, could be extended to include most items subject to corrosion. Figure 23 shows a batch of cowls and hatchway covers protected by metallizing with zinc. Many complete steel launches have been treated in this manner, and ship's lifeboats of all-steel construction with their constant exposure to heavily salt laden atmosphere provide another excellent example of the usefulness of the process.

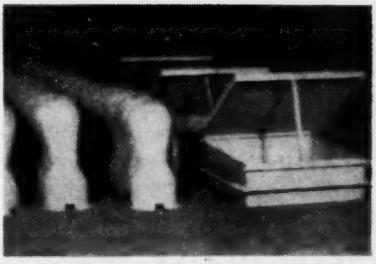


FIG. 23—Batch of cowls and hatchway covers protected by metallized zing coating.

This paper seeks to stress both the limitations and usefulness of metal spraying in shipwork, so that those who would use it may be justifiably confident. If such knowledge sometimes enables a chief engineer to expedite a repair, or a shipyard executive to give better service to shipping, then these notes on the marine engineering aspects of metallizing will have fulfilled their purpose.

HEAT-RESISTANT ALLOYS FOR AVIATION

ACKNOWLEDGMENT

This article is reprinted from the August 1949 issue of "Aero Digest." It was written by F. S. BOERICKE of the Haynes Stellite Co. It covers numerous high temperature alloys, their uses, and their performance in specific applications.

Jets, rockets and supersonic speeds are putting the metallurgists and alloy suppliers "on the spot." In the 1920's and 1930's the temperature range of 800 to 1200° F. was considered high for highly-stressed parts. Steam turbines, mercury-vapor turbines and some parts of reciprocating engines required stressed alloys to withstand these temperatures. In this decade, however, these temperatures are rapidly becoming the low end of the range for heat-resistant alloys; highly-stressed parts are being used at continuous temperatures of 1500° F and above.

The term "superalloys" has been used in recent literature to describe a number of heat-resistant alloys specially developed to meet these higher temperatures. As yet, no clear definition of a superalloy has been made. For the purpose of this discussion, let us consider superalloys as those alloys that have physical properties considerably better than those of stainless steels in the range of 1200 to 2000° F.

In speaking of improved physical properties, reference is made not only to strength values—such as ultimate, yield, creep, and stress-rupture strengths—but also to such corrosion factors as elevated-temperature oxidation and resistance to carburization. The so-called superalloys are rapidly proving their worth in many applications in the aircraft industry and other industrial fields where these factors must be taken into consideration.

Fig. 1 presents an idea of the strength of some of the newer alloys, showing 100-hour stress-rupture values as a function of temperature for several common alloys, in comparison with those of some of the special Haynes heat-resistant alloys. Reading this graph at 1400° F., for instance, we find that low-carbon steel would break in 1000 hours if loaded to about 1000 psi; 18-8 (Type 302) at 5000 psi; 18-8 plus Mo (Type 316) at about 12,000 psi; while the *Haynes* superalloys could withstand stresses in the order of 17,000 to 30,000 psi.

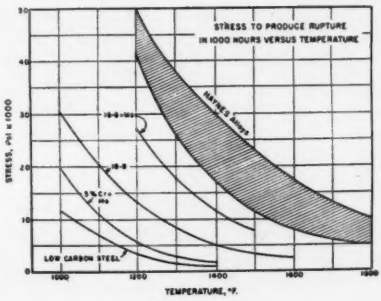


FIGURE 1.

Short-time tensile strengths for the *Haynes* alloys are considerably higher than these 1000-hour values. At 1500° F, for example, the superalloys have short-time tensile strengths of about 40,000 to 80,000 psi; and at 1800° F. they range from about 20,000 to 40,000 psi. The oxidation resistance of these alloys is considerably better than the 18-8 variety of stainless steel, which scales rather quickly at temperatures above 1650° F. Most of the superalloys do not oxidize rapidly until temperatures considerably in excess of 2000° F. are held continuously. Exceptionally good resistance to carburization is also a common characteristic of most of them.

The *Haynes* high-temperature alloys fall naturally into three groups:

Group A—Cobalt or cobalt-nickel base alloys: *Haynes Stellite* alloys Nos. 21, 23, 27, 30 and 31; *Haynes* alloy L-605

Group B—Nickel-base alloys containing tungsten or molybdenum: *Hastelloy* alloys B and C

In order to compare these alloys with more common materials of construction, a fourth group should be considered:

Group D—Modified stainless steels and nickel-base alloys without strengtheners: 18-8 Cb (Type 347) stainless; 18-8 Ti (Type 321) stainless; 25-20 (Type 310) stainless; 18-8 Mo (Type 316), etc. Generally, the Group D alloys will fall between the Type 302 and Type 316 strength curves on the graph shown in Fig. 1. Groups C, B, and A fall progressively higher in the shaded band of this chart. The high-temperature strengths, both short-time and long-time, become progressively greater going from Group D through Groups C, B, and A.

In addition, this grouping of alloys serves to indicate the relative ease of forming and fabricating; those at the bottom of the list, which have lower strength and hardness and greater ductility, are naturally somewhat easier to bend, stretch, press and spin. In general, considering all the alloys in their fully annealed condition, there is a trend toward higher room-temperature strength and less elongation and ductility—as well as a greater tendency toward work-hardening—in progressing up the list from bottom to top. *Haynes* alloy L-605 is an exception to this rule, since its ductility and formability are comparable with those of the Group C Alloys.

Recent articles have discussed the techniques used for welding and fabricating these heat-resistant alloys. They have described procedures and practices used for producing clean, strong welds by several methods: resistance

welding (spot or roller-seam), oxy-acetylene, metallic-arc, and atomic hydrogen welding — also *Heliarc* and *Unionmelt* welding (both processes of The Linde Air Products Co.). On the whole, welding by these methods differs little from the techniques used for Type 347 stainless steel.

HANDLING TECHNIQUES.

Among the techniques that have been used for fabricating these alloys are drop-hammer stamping, press-forming, spinning, stretch-forming, machining, drilling, shearing and punching. Figure 2 shows a stamped part for an exhaust manifold, formed out of N-155 alloy by a drop hammer. In general, for a difficult forming operation such as a deep draw or a severe drop-hammer operation, the technique used for the N-155 alloy (Group C) would differ very little from that used for Type 347 stainless steel (Group D). However, the same part fabricated from one of the group B alloys might require about twice as many intermediate anneals as the stainless steels. Of the Group A alloys listed above, only *Haynes* alloy L-605 is commercially available as sheet, bar and rod. This alloy can be classed with *Multimet* alloys when describing weldability and formability.

The most publicized example of a successful application of superalloys was the amazing development and production of blades for aircraft-engine turbosuperchargers during the war. The need for these superchargers was so acute that Haynes Stellite Co. was producing more than 2,000,000 blades per month by the precision-investment casting process. The investment-casting process has been used successfully also for making blades for virtually every production and research gas turbine in the country.

The blades in the Allison J33 turbojet (recently certificated by the CAA for commercial use) are made from *Haynes Stellite* alloy No. 21, sometimes known as *Vitallium* (trade-mark of Austenal Laboratories, Inc.). Other production and research engines are also using this alloy and other cobalt-base superalloys such as *Haynes Stellite* alloys Nos. 23, 27, 30, and 31.

A gas-fired cabin heater manufactured by the Stewart-Warner Corp. had an average life of 400 hours when

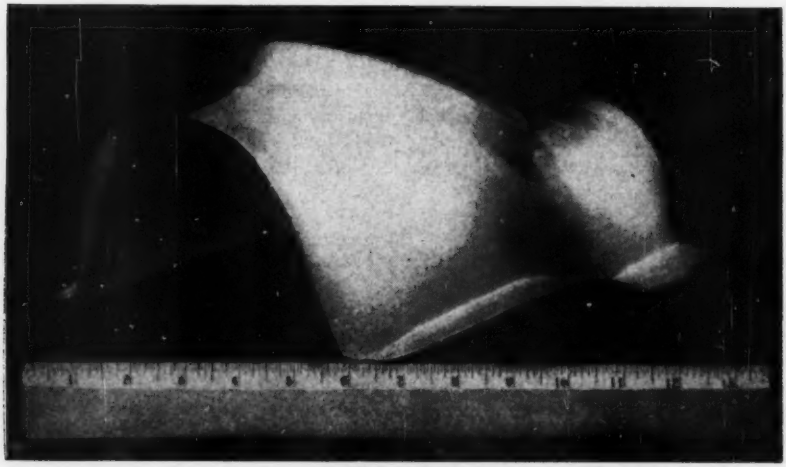


FIGURE 2.

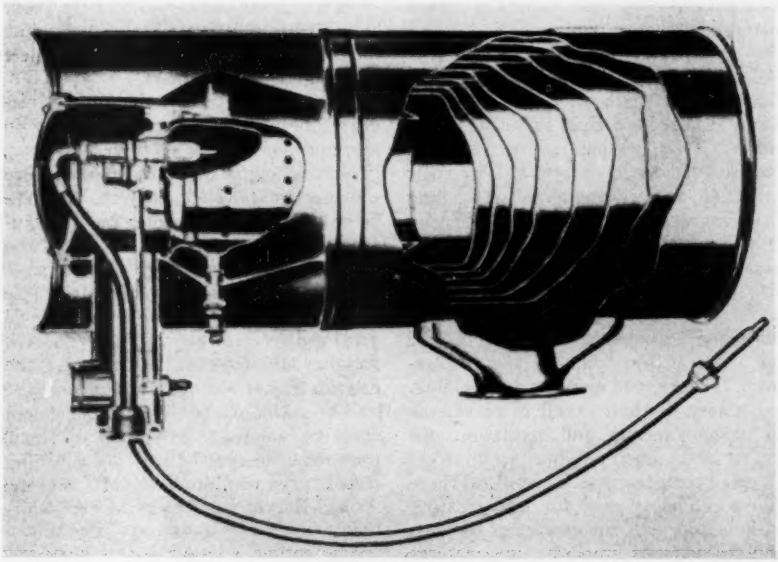


FIGURE 3.

manufactured from Type 347 stainless steel. When fabricated from *Multimet* (N-155) it was still in good service after 1340 hours. This company is manufacturing its No. 921 *Southwind* cabin heater of N-155 alloy (Figure 3), and reports successful installations in the following airplanes: the Boeing B-50, 377 *Stratocruiser*, XB-47 and C-97; Lockheed P2V2; Grumman XJR2F-1; Martin 202; North American P-82; and Beech Model 34. Stewart-Warner now guarantees the N-155 cabin heater for 1000 hours.

Another outstanding use of this N-155 alloy is in a steam boiler-type cabin heater, such as that used in the Douglas DC-3. This heater formerly lasted 150 to 300 hours, averaging about 200 hours. It is operated by having water converted to steam by the hot exhaust gases, which pass longitudinally through the inside liner. The water is introduced into the annular chamber between the inner and outer shell. By converting only the inner liner to N-155 alloy (Figure 4), two boilers have been flown for over 2000 hours before failure. Thus, an increased cost of some 20% to 30% has resulted in an increased life of about 1000%. This unit is subjected not only to high temperatures and oxidation, but also to severe thermal shock, since the boiler is frequently run empty until

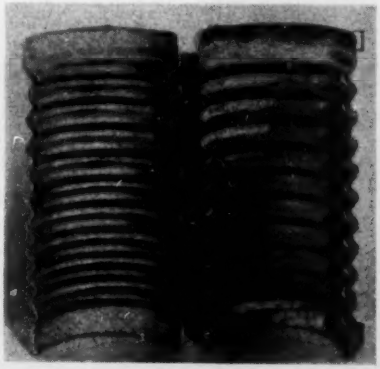


FIGURE 4.

heat is needed in the cabin, at which point cold water impinges directly on the red-hot inner liner.

Both Douglas and Solar Aircraft Co., received such favorable comment from test boilers that Solar made up some 200 for this past winter's service. Repeat orders have attested to their remarkable performance. The tooling that was used formerly for fabricating this part from 347 stainless is now being used without modification for the present N-155-alloy boilers. The joining of N-155 alloy with itself or with 347 stainless is being performed on a production basis by spot, roller-seam, *Heliarc,* and metallic-arc welding.

Because of their excellent resistance to carbon pickup and oxidation, together with their higher strength at elevated temperatures, several of these alloys are being used for heat-treating baskets and pots, for cyaniding baskets, and for various brackets, jigs, fixtures and handling equipment in heat-treating plants. *Multimet* and *Hastelloy* alloy A have lasted from 20 months to two years in a cyanide bath at 1500° F., as compared with three months for stainless steel and two weeks for SAE 1020 steel. *Hastelloy* alloy C and N-155 alloy show a rate of carburization only about one-third as fast as stainless steel, while the cobalt-base alloys are virtually inert to carburizing conditions.

Since conventional piston-type aircraft engines have been increasing in size and horsepower from year to year, greater amounts of higher-temperature exhaust gases have had to be combatted. Several companies have manufactured collector rings of some of the superalloys for handling exhaust gases. It is too early to say which of these alloys will give the most economical service life. However, in view of the weight saving made possible by the use of higher-strength alloys and the lower maintenance and replacement costs of longer-lived collector rings, the experimental rings now being tested are of interest both to the Armed Services and to commercial airlines.

The collector ring for the Lockheed P2V2, shown in Figure 5, incorporates the principle of jet augmentation, which gained an additional 25 mph of speed. The jets are individual castings made by the precision-investment process and are welded to the sheet-metal manifold. These castings were made in both

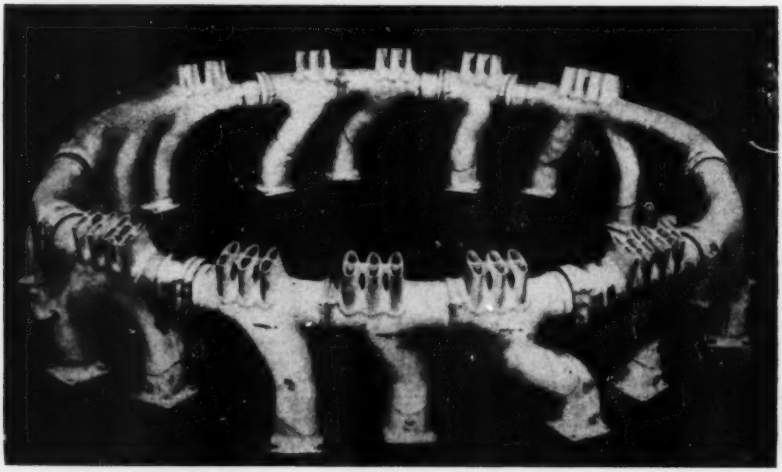


FIGURE 5.

Hastelloy alloy C and *Haynes Stellite* alloy No. 21. Precision-investment casting thus has proved to be a useful tool for manufacturing parts that are difficult to fabricate in sheet metal alone.

GROWING HEAT PROBLEMS.

As the temperatures of jet engines rise from year to year, it becomes increasingly apparent that not only the highly-stressed rotating blades must be made of superalloys, but also the attendant sheet-metal parts — such as combustion chamber liners, diffuser rings, inner and outer tail cones, and exhaust tailpipes. Several of the jets are notorious for their relatively short-lived combustion-chamber liners. These liners become distorted, cracked and buckled after they have been in service between 10 and 50 hours. Several of the superalloys have been tested in sheet-metal form for these applications and have given marked increases in service life. As temperatures in the combustion chamber build up with newer and more powerful modifications of these engines, it is probable that liners can no longer be made from the steels now used.

Many of the jet fighters and bombers had to renew tail cones and tailpipes every 25 or 50 hours when they were made from Type 347 stainless steel. Figure 6 shows tail cones made of N-155 alloy and *Hastelloy* alloy C that are still serviceable after 150 to 200 hours. They were replaced in the North American XB-45 four-engine jet bomber because of a design change, although examination shows that they are suitable for many hundreds of hours of further use. Prior to the installation of these alloys, cones of 347 stainless steel of slightly heavier gage had consistently failed because of buckling and cracking after an average of about 25 hours' life. This bomber also has tailpipes made of N-155 alloy that have virtually eliminated the need for replacement. Other similar installations on jet planes are equalling this performance.

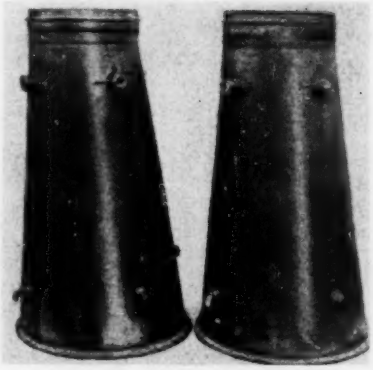


FIGURE 6.

In the rocket field, also, various heat-resistant alloys have been and are being tested. It is too early in the test programs to state conclusively which alloy is best of each application. Results thus far indicate that some of these superalloys will find their way into rockets, ramjets and pulsejets.

Most of the applications described here have been fabricated and tested since the end of the war. In every case, a part that was formerly made of stainless steel was duplicated in the chosen superalloy with only minor changes in practices. In every case, also, the use of a superalloy has been justified economically, in spite of its slightly higher cost, because of the marked improvement in the service life of the part. There is little doubt that these versatile materials of construction will find increasing uses both in high-speed aircraft and in high-temperature applications in industrial fields.

However, engineers are continually increasing their demands for alloys that will resist even higher temperatures. The Research Department of Haynes Stellite is devoting much time, money, and effort to develop new alloys that will be ready for the advance into the next temperature decade.

THE OPPOSED PISTON DIESEL ENGINE.

ACKNOWLEDGMENT.

This article, is an excerpt of a paper presented before a chapter of the Society of Naval Architects and Marine Engineers at San Francisco in January, 1949, by H. G. NAGEL, Fairbanks Morse & Co. It is reprinted from the "Pacific Marine Review" for March, 1949. It discusses the characteristics and application of the opposed piston diesel engine.

The first Fairbanks Morse Opposed Piston diesel engines were built in 1934. The first engines built attracted the attention of the Navy, which found the engine so well suited to its needs, particularly in submarines that, with the exception of a few experimental engines applied to railroad service, the entire production of this type of engine went into Naval applications. Approximately three million horsepower were installed in various types of Naval vessels.

Since the end of hostilities some of these engines found their way back into commercial use either as individual engines, salvaged from vessels cut up for scrap, or as power plants in complete vessels which have been converted to commercial service. The engines are also in general factory production in commercial ratings which differ somewhat from the Naval ratings.

Because the production of the engines was confined to Naval use for so many years, little general information was published, and the general public has had little chance to become acquainted with its characteristics. The purpose of this paper is to explain the details of construction and operation of this engine, which are quite different from those of conventional diesel engines.

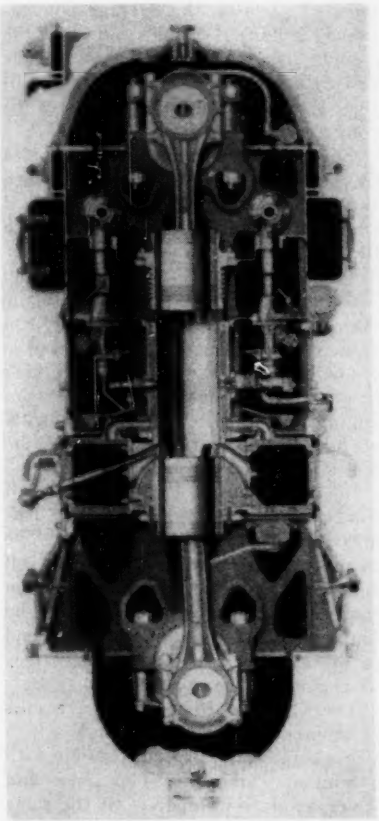
In the early 30's the Fairbanks Morse engineers sensed the need for a completely new approach to the design of a heavy duty, general purpose engine in the horsepower range up to 2000 h.p. Consideration was given to vertical types, V-types, double acting, and all other assembly formations. The final choice went to the 2 cycle, Opposed Piston, vertical, inline construction as having the greatest possibilities of accomplishing the desired reduction in

weight and higher operating speeds, and at the same time retaining the simplicity, and reliability, and low fuel and lubrication oil rates, demanded by the user.

As currently constructed, the engine is built in 8⅛" bore and 10" stroke on each piston. The engine has been built in 5, 6, 7, 8, 9, and 10 cylinder assemblies, and we are now beginning on a 12 cylinder engine.

The most common engine is the 10 cylinder size, which the Navy rated up to 2000 h.p. at 850 rpm. In railway service we take off as high as 2150 h.p. from the same engine, but for general commercial purposes we rate the complete line of engines at 160 h.p. per cylinder at 720 rpm, to assure the user of ample reserve power. This results in ratings on the commercial engines of 6 cyl. 960 h.p., 8 cyl. 1280 h.p., 10 cyl. 1600 h.p., and 12 cyl. 1920 h.p. In adapting engines from surplus to commercial service, we recommend rating on this basis in the interest of maintaining a conservative reserve power.

The Opposed Piston principle is not new. Some of the earliest patents date back as far as 1880, when the principle was first applied in the development of gas engines. The fundamental design of the Opposed Piston engine is based on the use of a plain open ended cylinder in which two pistons, operating in opposite directions, approach each other at the center of the cylinder to form a combustion space between the pistons. Air trapped between the pistons is compressed as in the conventional diesels, fuel is injected at the proper time and is ignited by the heat of compression. The burning gases expand and force the pistons to move in opposite directions away from center, forming the power stroke. At the end of the stroke scavenging ports are opened, discharging the exhaust gases to the exhaust manifold and recharging the cylinder with air. Operating on the



Fairbanks Morse Model 38D8-1/8 opposed piston Diesel engine. End cross section.

2 cycle principle, the engine develops a power stroke for every crankshaft revolution. The engine is fitted with two crankshafts and power generated by the upper pistons through the upper crankshaft is transferred to the lower crankshaft by a vertical connecting shaft with bevel gear drive.

No Cylinder Head.

The Opposed Piston design has a number of key advantages. The first and most obvious feature is the absence of cylinder heads. The cylinder head is one of the complex and highly

stressed parts on the average conventional engine. Elimination of the cylinder heads eliminates head gaskets and cylinder head fits which are subjected to the heat and pressures of combustion.

Elimination of head also eliminates the non-working parasite gas pressure thrust against it. In the conventional engines, the combustion forces create the same upward thrust on the cylinder head as downward thrust on the piston. This upward thrust tends to lift the entire head, cylinder and frame and results in rocking vibration in the frame. It is the equivalent of the kick in firing a gun. In the Opposed Piston engine this thrust is converted to a useful force operating against the opposite piston.

In the Opposed Piston engine all combustion forces are completely balanced between the two pistons. The cylinder liner is entirely free of all end thrust in either direction of piston travel. The liner is held in place by four light cap screws in lugs at one end of the cylinder and is completely free to expand at the opposite end.

The Opposed Piston design results in inherent mechanical balance which makes high rotative speeds possible with a minimum vibration. The upper and lower crankshafts operate at the same speed and have the same stroke. Since all reciprocating parts always move in opposite directions, the resulting inertia forces cancel each other almost completely, and a smooth running engine is obtained without the use of counterweights.

Scavenging air is provided by a Roots type, three lobe, scavenging blower mounted on the after end of the engine and driven from the upper crankshaft. This blower has a capacity of 40% more delivered air than the combined displacements of all of the cylinders in the engine. Under normal operating conditions the scavenging air manifold pressure is approximately 3 lbs. per sq. in.

The air ports in the upper end of the cylinder liner are controlled by the upper piston. The exhaust ports at the lower end of the liner are controlled by the lower piston. The timing of the opening and closing of these ports is controlled by the relative timing between the two crankshafts, the lower crankshaft leading the upper crankshaft by 12 degrees in normal "forward" rotation. This lead provides the proper sequence in opening and closing of the exhaust and air ports, and allows a period for supercharging the cylinder.

During the compression stroke, after the air and exhaust ports have been closed, the pistons move toward the center of the liner, compressing the trapped air at a 16 to 1 compression ratio. At the proper timing at inner dead center, fuel is injected between the pistons, and the pistons then move away from each other on the expansion stroke.

At approximately 124 degrees after inner dead center, based on the rotation of the lower crankshaft, the lower piston will begin to open the exhaust ports. The residual gas pressure within the cylinder is discharged into the exhaust manifolds on each side of the engine, dropping the pressure within the cylinder to practically zero.

At approximately 140 degrees after inner dead center, also based on rotation of the lower crankshaft, the upper piston begins to open the air ports, and scavenging air at about 3 lbs. pressure is blown into the upper end of the cylinder. The shape of the ports is such that a whirling motion is imparted to the entering air.

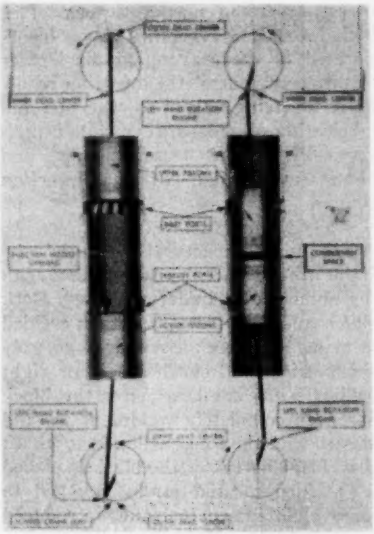
The ports are also cut at an angle to the vertical center line of the cylinder to create a solid slug of air covering the entire area of the cylinder bore. This creates practically a solid mass of air in the upper end of the cylinder liner which moves downward forcing the burned gases out of the exhaust ports. Since the scavenging air blower delivers 40% more air than the volume

of the cylinders, there is a complete follow through of fresh air behind the exhaust gases assuring positive scavenging of the cylinders and a complete recharge with clean fresh air.

The combustion chamber is created between the cup shaped crowns of the two pistons as they approach each other at inner dead center. During the compression period, the air continues its whirling motion creating extreme turbulence within the air combustion space.

Each cylinder has two conventional spring-loaded injection nozzles located diametrically opposite each other on each side of the engine, each nozzle being controlled by an individual injection pump. Each nozzle has a three hole tip and injects the fuel to one side of the combustion chamber into the whirling air supply. Since the combustion chamber is formed between the crowns of the two pistons, its shape is completely independent of the limitations imposed on conventional engines by cylinder heads where the structural strength of a head, location of valves, etc., create complications. Also the cup shaped contour of the piston crowns protect the cylinder walls from the initial flash of heat at the beginning of combustion, by completely surrounding the combustion space at inner dead center.

The 12 degree difference in timing between the upper and lower crankshaft results in an unequal division of the power generated between the upper and lower pistons and their corresponding crankshafts. In normal forward rotation the upper crankshaft generates approximately 28% of the total indicated horsepower of the engine, and the lower crankshaft generates approximately 72% of the indicated horsepower. However, the upper crankshaft drives the scavenging blower and the injection pumps and other minor auxiliaries, which absorb part of this indicated horsepower with the result



Detail of piston action.

that the upper crankshaft actually delivers to the lower crankshaft only about 20% of the total brake horsepower output of the engine.

The two crankshafts are coupled together through a vertical transfer shaft and helical beveled gear drive, through a spring cushioned coupling and special timing adjusting joint. Each pinion shaft is supported by a large roller bearing immediately behind the pinion and by a thrust bearing at the coupling end of the shaft. The spring coupling compensates for expansion in the engine frame and the shaft, and also gives torsional flexibility between the crankshafts. Timing between the two crankshafts is adjustable through a special tapered clamp coupling immediately below the spring coupling by which timing between the two crankshafts can be shifted easily.

Direct Reversing Marine Service.

Since this engine was designed to be universally applicable, its design incorporates the necessary features for

direct reversing marine service. This includes special reversing valves incorporated in the scavenging air blower to properly control the direction of air flow, reversing valves for the fuel and lubricating oil pumps, reversible centrifugal circulating water pumps, and automatic shifting of the injection timing.

Multiple Cylinders.

The main structural parts of the frame are assembled in accordance with the number of cylinders required. Deck plates and side plates are then welded in place. The block assembly is entirely symmetrical and can be used for right or left hand engines. After the block has been completely welded, it is sand blasted and then magnefluxed to check all welds. Thereafter the block is placed in a furnace and stress relieved to remove all internal strains introduced by the welding process. Thereafter machining is handled by conventional processes.

The removable cylinder assemblies are bolted into the block by lugs at the upper end of the liner. The lower end is completely free to expand and is held in place by a slip fit through the exhaust deck. The construction of the liners is such that jacket water never touches the frame, and there should never be any corrosion to any part of the frame to cause sticking of the liners, or leakage of water to the crankcase.

The liner proper is cast of special alloy iron, resulting in liner hardness of better than 300 Brinnell.

Pistons are of the trunk type, completely oil jacketed and oil cooled by lubricating oil delivered from the main oil header through main bearings, connecting rod bearings, drilled connecting rod and wrist pin bearings. The piston assembly is of two piece construction consisting of an insert which supports the wrist pin assembly and bushings and, in turn, is held in the separate outer piston shell by four studs. The piston shell is a uniform casting of even wall thickness around its entire circumference since all wrist pin bosses and supports have been eliminated from the shell. This does away with the tendency of the piston to change its shape as a result of heat distortion and internal stresses, and entirely eliminates the possibility of wrist pin scoring of the cylinder wall.

The space between the piston and the insert forms a lubricating oil jacket through which the lubricating oil is circulated to effectively cool piston crown, ring belt and complete skirt area. The cooling oil circulates through the crown of the piston and through the piston walls, and is discharged through a nozzle to the respective crankcases. Positive cooling of the piston relieves the piston rings of any tendency to stick, which results in maintaining an effective seal of combustion pressures.

The fuel injection system is built entirely by Fairbanks, Morse & Co. Each cylinder has two injection pumps and two injection nozzles. The pumps are unique in that they operate in an inverted position, being suspended below the camshaft. Fuel under 20 lbs. pressure is fed continuously to the injection pumps by a fuel transfer pump. The injection system is completely selfventing.

Pumps are of the conventional helical plunger type, operating with variable beginning of injection timing and fixed ending.

Woodward governors control the injection, adjusting both gangs of the pumps simultaneously. Particularly in locomotive service, but also available for other applications, where long idling periods are required, a special linkage arrangement is available which cuts out one bank of pumps faster than the other, when approaching slow idling speed, so that injection finally takes place from one pump and nozzle only. This results in clean combustion

and improved economy where long idling periods are involved, such as on fishing boats, or where large auxiliary sets may be required to run for long periods at extremely low load factor.

The direct reversing marine engine has a safety interlock system incorporated in the maneuvering controls to positively prevent the injection of fuel to the cylinders if the engine is not rotating in the direction indicated by the position of the control shaft lever. When a vessel is underway there may be a tendency for the propeller to keep the engine turning over when the control lever is shifted to the stop position prior to reversing, or vice versa. A careless operator may throw the engine into reverse position before forward rotation of the engine has stopped, with the result that fuel will be injected, and even though the injection takes place entirely out of time, the engine may continue to rotate in forward rotation instead of reversing, thereby creating a dangerous condition. To prevent this, the safety device cuts off all injection until the engine is actually turning in the proper direction.

The fundamental interlock control is by this simple process, although a second interlock valve is tied in with the air starting system to quickly open the interlock valve for snappy operation of the control and fast maneuvering.

When the operator transfers the controls to the "reverse" rotation, or vice versa, the starting air is always released into the cylinders. If a propeller drag continues rotating the engine in the wrong direction, the starting air will act as a brake and quickly stop the engine and change its rotation after which the interlock releases injection. Mechanical brakes operated pneumatically and automatically from the control shaft are also available.

With this interlock system it is impossible for the engine to operate in the wrong rotation. This was of particular advantage in combat vessels where an operator might become excited. It is a valuable safety measure in any commercial craft.

Speed.

The matter of speed is a point worth discussing. The real criterion is piston speed. Operating at 720 rpm each piston has a piston travel of 1200 ft. per minute. The total effect of the two pistons operating in opposite directions is to create a compression and expansion rate equivalent of 2400 ft. per minute, since the total travel is the sum in the travels of the individual pistons. In this way, the effect of a long stroke engine is obtained with the mechanical construction of the shorter individual stroke of each piston.

1200 ft. per minute piston speed is conservative by all present engine standards. Since the engine is in practically perfect mechanical balance by its opposed piston construction, and since its combustion forces are also in perfect balance for the same reason, the engine operates smoothly at 720 rpm commercial rating, or 850 rpm Navy and railroad ratings.

From a maintenance standpoint, the parts are much lighter and easier to handle than those of comparable slow speed engines. The following comparisons show the weights for two 1600 hp units:

	Model 38 Opposed Piston	*Model 33 Single Acting*
Bore and Stroke	8⅛x10	16x20
R.P.M.	720	300
No. of Cylinders	10	8
Weight of Cylinder, Lbs.	230	2870
Piston with rings, pin and bracket	82	735
Connecting Rod with bearings and bolts	79	590
Crankshaft (lower)	1700	10,800
Cylinder head	None	685

The lighter weight of the parts makes routine inspection and servicing possible with a minimum of shutdown time as one man can handle the complete piston and connecting rod assembly without the use of heavy tackle.

The question naturally arises as to how this engine can be applied in marine service.

The Navy used the engine in practically every conceivable combination of direct drive, reduction gear drive, multiple engine drive, electric drive and combinations of electrical and mechanical drive.

In the LSM vessels direct drive through hydraulic couplings to 720 rpm propellers was used. In the PC boats twin engine, twin screw installations were made, each engine driving a separate propeller through a horizontally offset reduction gear. Submarines used various combinations of direct gear drive and electrical drive, or all electric drive. Aircraft tenders used four engines on twin screw drives, two engines being coupled to one reduction gear driving one propeller. Destroyer escort vessels used similar four engine, two propeller drives.

MULTIPLE UNIT—SINGLE SCREW.

Through the use of two pinion reduction gears, it is possible to couple two, three, or four engines to a single propeller shaft. Connection may be direct through flexible couplings, or through hydraulic or electric couplings according to the requirements of the job. Insofar as the gears are concerned, hydraulic couplings are not necessary. Such a drive would be used with either eight, ten or twelve cylinder engines in which the overlap of power strokes on each revolution of the engine is so close that there is practically a steady flow of power. The 12 cylinder engine has 12 power strokes per revolution, spaced at 30 degree intervals. At 720 rpm, this is at the rate of 8640 power strokes per minute, or 144 impulses per second per engine. Proper positioning of the keyways in the couplings permits dividing timing between the engines, so that the engines would fire alternately, splitting the timing between impulses to even a shorter period.

A straight gear drive without hydraulic couplings introduces only a 2% loss in the reduction gears, which can be readily recovered by improved propeller efficiency. Two 10 cylinder engines normally rated at 1600 hp at 720 rpm would have a combined rating of 3136 shaft hp at 169 rpm propeller speed. Total weight of the assembly would be approximately 105,500 lbs., or roughly 34 lbs. per hp for two engines with accompanying gears.

A two engine unit with hydraulic couplings would have a combined rating of 3040 shaft hp and an overall length of a fraction over 24 ft. and a width of slightly less than 12 ft. Height above the shaft centerline to the top of the engine is only 7½ ft. or 8 ft. 7 inches clearance for pulling liners.

A quadruple drive consisting of four 10 cylinder, 1600 hp engines, totaling 6400 rated hp would deliver 6272 hp at 139 rpm propeller speed at a weight of 211,000 lbs. for engines and gears, or approximately the same weight per hp.

Using the latter quadruple drive with hydraulic couplings, or electric couplings, the shaft horsepower would be 6,080 as the couplings would introduce an additional 3% loss. Such a combination of four engines with reduction gears for a 90 rpm propeller speed would weigh approximately 233,000 lbs., or roughly 38 lbs. per hp. A four engine drive, capable of 6080 shaft hp per unit, would have an overall length of approximately 43 ft.

Using 12 cylinder engines, the total horsepower would be 7300 with hydraulic couplings, or 7528 hp without couplings, useing four engines per screw, or a total of approximately 15,000 hp twin screw.

The low head room and light weight of these units makes it possible to eliminate a lot of lost space in the engine room trunk required for the larger slow speed units, thereby providing both increased space and increased weight capacity for greater pay load.

Comparable electric drives would deliver approximately 5500 shaft horsepower from a similar group of four 1600 rated hp engines. Electric drive introduces practically a 15% loss between the engines and the propellers. Unless there is some very great advantage to be obtained from maneuvering characteristics of the electric drive, the additional weight and cost is not generally warranted. Four engine electric drive would weigh approximately 442,000 lbs. including engines, generators, motors and control, or a weight of approx. 80 lbs. per shaft horsepower, or more than double the weight of a comparable direct gear drive. The direct gear drive with electric couplings will practically equal the performance of the all-electric drive insofar as maneuverability is concerned, and will improve the fuel consumption approximately 10% by its overall efficiency of approximately 95% as compared with 85% for the electric drive.

The direct gear drives do not necessarily have to be installed with all engines on the same horizontal plane. Gears can be built permitting installation of one engine at a higher level than the other conforming to the contour of the hull. The destroyer escorts, for example, had four engine, twin-screw drives with each pair of engines located in a separate fore or aft engine room. The outboard engines were set approximately 2 ft. higher than the inboard engines, and because of the change in contour of the fine line hull, the port and starboard gear assemblies were built with different elevation combinations, because of the change in contour of the hull at the fore and aft engine rooms.

With today's present high cost of construction, it is imperative that vessels be kept in operation with a minimum of shutdown time. Passenger vessels are operating on extremely fast turn-around schedules, which allow no time for machinery overhaul. Several passenger vessels have recently been designed for routes where a single vessel on the run has to operate continuously on seven day schedules without provision for tie-up for service. These schedules called for one vessel to operate seven days per week, three hundred and sixty-five days per year.

Multiple engine installations were specified for the express purpose of allowing one engine to be overhauled, if necessary, without interrupting the schedule of the vessel. Normally, all engines would be in operation, but shut-down of one engine would not seriously reduce the speed of the vessel.

Following the rule of thumb that the horsepower required to drive a vessel varies as the cube of its speed, and allowing for the necessary reduction in speed of the engines with corresponding drop in the nominal horsepower rating, it would be possible to maintain approximately 87% of the normal speed operating on three engines of a four engine group without exceeding the normal rating of the engines. Allowing engines to operate at 10% overload, 91% of schedule speeds could be maintained.

Based on two engines approximately 71% speed can be maintained on one engine without overloading, or approximately 74% speed could be maintained within a 10% overload.

These ratings are based on reducing the speed and nominal ratings of the operating engines in accordance with the reduction in the hull speed. With

such combinations schedules can be continuously maintained without difficulty.

It is our hope that this discussion of the Fairbanks, Morse Opposed Piston engine will result in a better understanding of its characteristics and application, and will show how it has been possible to build an engine incorporating all the desirable features of reliability and economy of the slow speed engine, without the disadvantages of heavy weight and large size.

THE EFFECT OF PHASE ERRORS IN TIME-BASE INDICATOR DIAGRAMS.

ACKNOWLEDGMENT.

This article by T. D. WALSHAW, D.L.C., B.Sc. (Eng.), A.M.I. Mech. E. is reprinted from "Engineering" for July 22, 1949. It discusses the source of error extraneous to the indicator by improper phasing, with particular regard to the magnitude of such error.

The pursuit of accuracy in the indicating of internal-combustion engines has led to the almost universal adoption of the "time-base" indicator, in which the pressure in the engine cylinder is plotted—either by the indicator itself or from observations—on a basis of crank angle or time. These indicators are now used even when the speed of the engine is low enough to allow the application of the conventional piston indicator. Even in the case of steam engines, the use of the time-base indicator is not unknown, and the new mobile test plant of British Railways is equipped with a Farnborough indicator. The modern cathode-ray indicator is an instrument of great accuracy, and when the latest technique of pressure plotting is employed, an accurate diagram of pressure against time is purely a matter of careful routine.

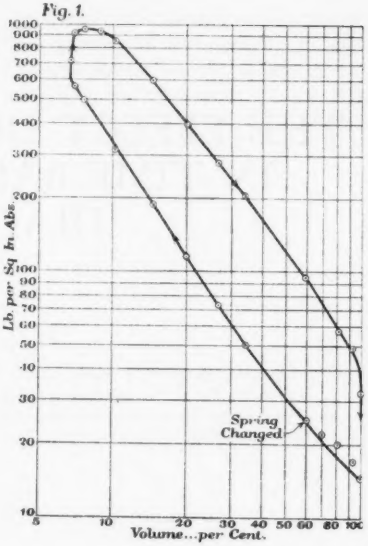
When, however, the pressure-time diagram is to be converted to a conventional pressure-volume diagram, or when twisting moments are to be estimated, a source of error extraneous to the indicator is introduced. Unless the reference mark on the diagram corresponds exactly with top dead center of the engine piston, an accurate conversion cannot be made. This fact has been known since the time-base indicator was introduced, and some care is always used in phasing such instruments. So far as the author is aware, however, no information has been published showing the magnitude of the error introduced. These errors are large, and it is probable that considerably more care is necessary both in the determination of top dead center and in the coupling of the drive to the time-base of the indicator.

This investigation was made when an engine had been indicated in which some unavoidable backlash was present in the indicator drive. Figures for I.M.E.P. were very erratic, and in one case worked out less than the brake M.E.P. A Farnborough diagram was therefore selected in which the rate of pressure rise was high—about 80 lb. per square inch per degree of crank angle—and with a high I.M.E.P., as it was considered that such extreme con-

ditions would accentuate the error. (At the same time, it should be noted that the I.M.E.P., though high, is in fact exceeded by a few commercial engines.) This diagram was then plotted on axes of log pressure and log volume — Fig. 1 — and any irregularities smoothed out. A new pressure-time diagram was then constructed—Fig. 2 —for use as a reference diagram. This reference diagram was drawn on a base 30 in. long, with a corresponding pressure scale.

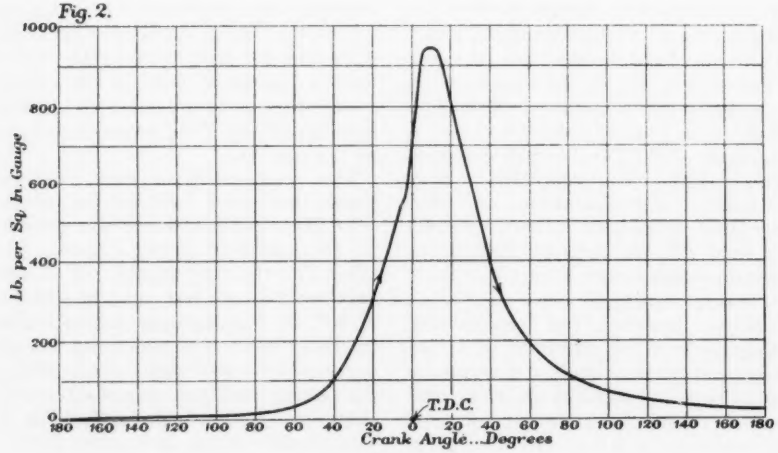
Using a connecting rod to crank ratio of four, a series of PV diagrams was constructed to a large scale, in which the diagram dead center was displaced relative to the engine dead center by different amounts. These PV diagrams are shown in Fig. 3. "Leading" diagrams are those in which the indicator reference mark is considered to be in advance of engine T.D.C., while "lagging" diagrams ran behind the engine. A cursory examination of Fig. 3 reveals considerable error. These PV diagrams were then planimetered, making allowance for the error in the squared paper on which they were plotted. (This error varied with atmospheric conditions, and in one case amounted to 1 part in 100.) Table I shows the results obtained.

Fig. 1.



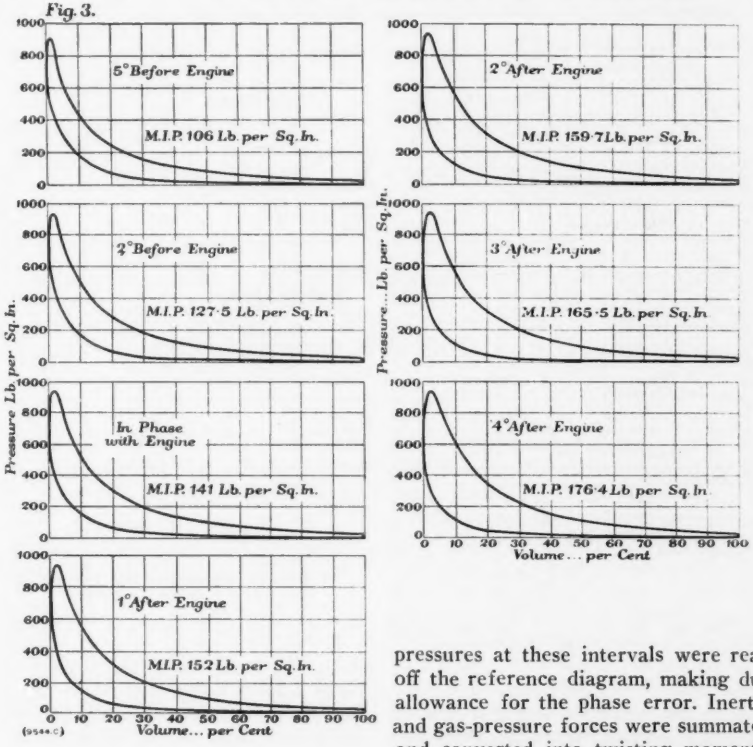
The mean error per degree of phase error is thus 7.82 lb. per square inch, or 5.5 per cent.

Fig. 2.



PHASE ERRORS IN INDICATOR DIAGRAMS.

Fig. 3.


5° Before Engine
M.I.P. 106 Lb. per Sq. In.
2° After Engine
M.I.P. 159·7 Lb. per Sq. In.
2° Before Engine
M.I.P. 127·5 Lb. per Sq. In.
3° After Engine
M.I.P. 165·5 Lb. per Sq. In.
In Phase with Engine
M.I.P. 141 Lb. per Sq. In.
4° After Engine
M.I.P. 176·4 Lb. per Sq. In.
1° After Engine
M.I.P. 152 Lb. per Sq. In.
Pressure Lb. per Sq. In.
Volume... per Cent

In constructing twisting-moment diagrams a maximum inertia force of 187.5 lb. per square inch of piston area was assumed, and intermediate values were calculated at 10-deg. intervals, with additional values at 5-deg. intervals in the region of the dead center. The gas pressures at these intervals were read off the reference diagram, making due allowance for the phase error. Inertia and gas-pressure forces were summated and converted into twisting moments, again using a connecting rod to crank ratio of four. A piston area of 1 sq. in. and a crank radius of 1 in. were used for convenience, and gas-pressure forces were neglected during the idle revolution of the four-stroke cycle. The twisting-moment curves are plotted in

TABLE I.

Phase Error.	I.M.E.P., Lb. per sq. in.	Error, Lb. per sq. in.	Per cent. Error.	Error per Deg. Lb. per sq. in.	Error, per Deg., Per cent.
5 deg. lead	106	−35	−24·8	−7	4·96
2 deg. lead	127·5	−13·5	− 9·6	−6·75	4·70
0	141	0	—	—	—
1 deg. lag ..	152	+11	+ 7·8	+11	7·8
2 deg. lag ..	159·7	+18·7	+13·2	+ 9·35	6·63
3 deg. lag ..	165·5	+24·5	+17·4	+ 8·05	5·71
4 deg. lag ..	176·4	+30·5	+25·1	+ 8·8	6·24

PHASE ERRORS IN INDICATOR DIAGRAMS.

Fig. 4.

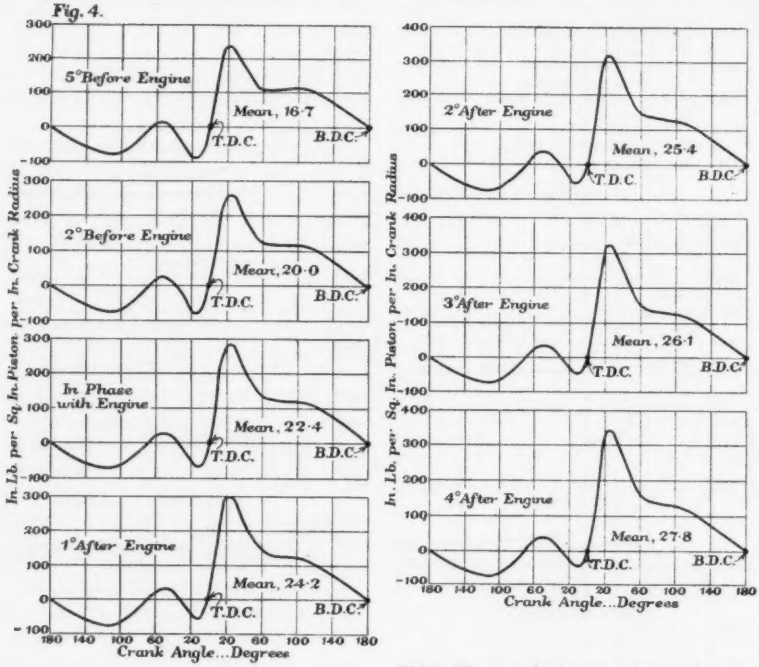


Fig. 4, the originals having a base 18 in. long. Selected curves are plotted on the same diagram in Fig. 5 in order to give a visual impression of the differences. The diagrams were measured by planimeter, making allowance for paper error as before. The results obtained are shown in Table II.

The mean error per degree of phase error is thus 4.95 per cent in the mean T.M., and 3.89 per cent in the maximum T.M. The variation in the ratio max.; mean T.M. is interesting, but is irregular when plotted against phase error. As will be seen from Fig. 5, there is also a considerable error in the "area of the largest loop" involved in flywheel calculations. For comparison, the columns showing I.M.E.P. and T.M. relative to 100 as the "correct" figure have been brought together in Table III. Fairly close agreement will be observed.

Knowledge of the harmonic components of the twisting-moment curve

TABLE II.

Phase Error.	Mean T.M. In.-Lb. per sq. in. per in.	Error, In.-Lb. per sq. in. per in.	Error per Deg. In.-Lb. per sq. in. per in.	Max. T.M., In.-Lb. per sq. in. per in.	Error, In.-Lb. per sq. in. per in.	Error per Deg., In.-Lb. per sq. in. per in.	Max. / Mean
5 deg. lead ..	16·7	−5·7	−1·14	234	−51	10·2	14·01
2 deg. lead ..	20	−2·4	−1·2	261	−24	12	13·05
0	22·4	—	—	285	—	—	12·72
1 deg. lag ..	24·2	+1·8	+1·8	298	+13	13	12·31
2 deg. lag ..	25·4	+3·0	+1·5	311	+26	13	12·25
3 deg. lag ..	26·1	+3·7	+1·23	324	+39	13	12·41
4 deg. lag ..	27·8	+5·4	+1·35	345	+60	15	12·41

Fig.5

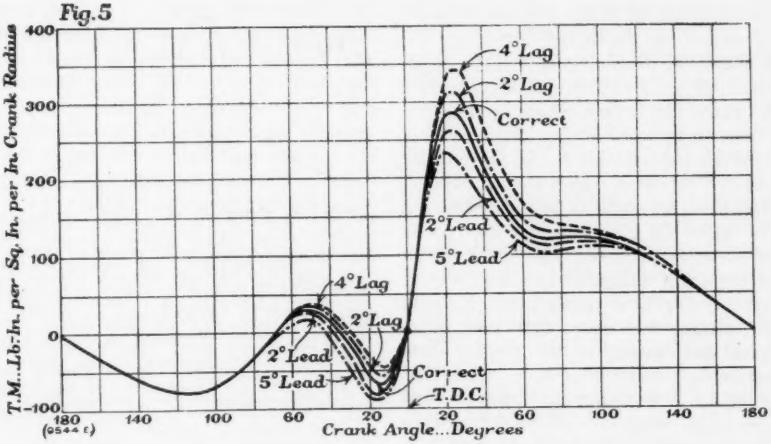


TABLE III.

Phase Error.	Relative Value. Correct = 100.		
	I.M.E.P.	Mean T.M.	Max. T.M.
5 deg. lead ..	75·2	74·5	82·1
2 deg. lead ..	90·5	89·3	91·6
0	100	100	100
1 deg. lag ..	107·8	108	104·6
2 deg. lag ..	113·2	113·5	109
3 deg. lag ..	117·4	116·5	113·7
4 deg. lag ..	125·1	124	121

is essential for the estimation of crankshaft stresses due to torsional vibration. It is, indeed, the need for more accurate knowledge of these components which has created much of the demand for more accurate indicating. As these components are made up of a gas-pressure component and an inertia component, added vectorially, it is evident that, quite apart from the error in the gas pressure T.M., the error should be some function of the phase error. It should be possible to compute mathematically the resultant error, but the operation is rather complex. As the ordinates of the combined T.M. diagram had already been determined, it was decided to analyse three of these —at 2 deg. intervals of phase error— using 36 ordinates over two revolutions, and extracting the first six, the eighth, and the twelfth harmonics. The results of this partial analysis were sufficient to indicate that serious error could result from the phase error, and further analysis was considered to be unnecessary. In Table IV are given values of A_n and ϕ_n when the T.M. curve is expressed in the form:—

TABLE IV.

Harmonic.	Leading 2 Deg.		Correct.		Lagging 2 Deg.		Error per Deg.	
	A_n.	ϕ_n.	A_n.	ϕ_n.	A_n.	ϕ_n.	A_n, Per cent.	ϕ_n.
1	44·5	−40 deg.	48·19	−36 deg. 48 min.	53·61	−34 deg. 57 min.	4·25 per cent.	1 deg. 16 min.
2	57·04	201 deg. 22 min.	61·22	203 deg. 22 min.	65·34	205 deg. 27 min.	3·4 per cent.	1 deg. 1 min.
3	51·02	98 deg. 12 min.	52·08	100 deg. 25 min.	55·25	102 deg.	2·1 per cent.	0 deg. 55·5 min.
4	29·33	183 deg. 15 min.	28·22	181 deg. 17 min.	26·28	179 deg. 42 min.	2·7 per cent.	0 deg. 53 min.
5	38·96	−98 deg. 48 min.	40·0	−98 deg. 11 min.	41·15	−87 deg. 51 min.	1·4 per cent.	0 deg. 14 min.
6	8·82	116 deg. 36 min.	9·33	120 deg. 18 min.	10·0	122 deg. 45 min.	3·16 per cent.	1 deg. 17 min.
8	21·42	−24 deg.	21·34	−25 deg. 13 min.	22·99	−25 deg. 53 min.	3·8 per cent.	0 deg. 28 min.
12	9·76	−33 deg. 54 min.	11·31	−38 deg. 54 min.	12·06	−43 deg. 28 min.	5·1 per cent.	2 deg. 23 min.

$$y = m + A_1\sin(\theta + \phi_1) + A_2\sin(2\theta + \phi^2) + \ldots\ldots A_n \sin(n\theta + \phi_n).$$

It should be noted that if β is the crank angle, $\beta = 2\theta$, as the T.M. diagram is drawn for a four-stroke engine.

The large error in the 12th harmonic —which corresponds to the sixth order critical speed in the case of a four-stroke engine—will be noted. Although the error in ϕ approaches the phase error in some cases, and the average of the eight examples is 1 deg. 3 minutes per degree of phase error, it would be unwise to draw any conclusion from this, owing to the limited data available, and the fact that the error in ϕ is sometimes positive and sometimes negative when referred to the phase error. Similarly, the errors in A_n follow no simple pattern. All that can be said is that a serious error in the harmonic components can be expected from quite small errors in the phasing of the indicator.

Unless the couplings are rigid, error is bound to result. In some cases, error may be present during part of the revolution only, or may change sign, especially on single-cylinder engines. The claw clutch of the Farnborough indicator is a persistent offender after the instrument has had some years use. In one case a combined coupling and clutch error of 2½ deg. was recorded. The popular vernier magneto type coupling can introduce error unless care is taken; something much more precise is required. It is an odd thing that test engineers will spend several hundred pounds on an indicator and yet rely on an eighteen-penny coupling to attach it to the engine.

In the case of the Farnborough indicator, an error is introduced if the spark shows a tendency to wander. On this instrument, the time scale is 25 deg. to 1 in., so that a spark scatter of 0.040 in. would cause an I.M.E.P. error of 5½ per cent on the diagram analyzed above. On some diagrams examined by the author, the pencil line is

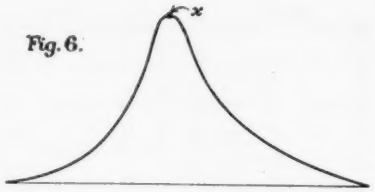
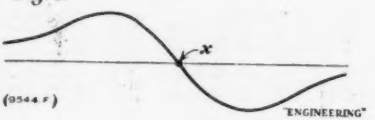


Fig. 6.

almost as thick as this, and the spark scatter often many times greater. On the cathode-ray type of indicator, the possibility of error is much greater if the X-axis is compressed, as is often the case when pressure plotting. The accuracy of the dividing of the degree-marker disc is obviously of supreme importance, but it is unlikely to be a serious source of error.

As the shaft of the engine is subject to torsional stress, shaft deflection is bound to exist. The error is unlikely to be large unless the indicator is driven through a fairly long length of stressed shafting. The determination of the T.D.C. is likely to be the most serious source of error, unless great care be taken. If, for example, any attempt is made to detect the actual "stationary" point of a piston at T.D.C., it will be found that a movement of as much as 8 deg. is possible in a small engine in taking up bearing clearances. Reliance on the parallelism of machined crankwebs is dubious, and no reliance should be placed on marks made on flywheels during manufacture, as the progressive errors are certain to be considerable. In the case of the cathode-ray indicator, use is sometimes made of the fact that the "rate of change" of pressure is zero at T.D.C. when the engine is not firing. Thus, in the case of the four-stroke, the diagram will appear as in Figs. 6

Fig. 7.



and 7, Fig. 6 showing the change of pressure with time and Fig. 7, the rate of change of pressure with time. The crossing point x is often assumed to indicate T.D.C. Unfortunately, the "base line" is not zero rate of change, but is the rate of change during the suction and exhaust strokes, and at T.D.C. this may be comparatively high.

Error may be reduced by careful attention once the possibilities are realized. Couplings should obviously have a minimum of flexibility—possibly the ideal type is the double Hardy coupling having discs of spring steel. This will allow a certain amount of mis-alignment without introducing much torsional deflection. The brake on the Farnborough indicator should be adjusted to take up the inevitable backlash in the clutch, if necessary supplementing its work by placing one hand on the drum while the diagram is being drawn. If any angular adjustment is considered to be desirable, this should be positive in action and capable of being locked.

Spark wander on the Farnborough indicator is often difficult to eliminate. Dirt in the disc-valve unit is the chief cause, and any attempt to overcome this by increasing the primary voltage will make matters worse. The disc valve should be kept scrupulously clean, and a careful watch should be kept on the lift of the valve and the condition of the spring. In the case of the cathode-ray indicators which use a similar type of indicating unit for calibration and pressure plotting, of course, cleanliness is vital, as the disc is very much lighter, and the lift much smaller. When pressure plotting on the C.R.O., the X-axis should obviously be as wide as possible, so as to increase the effective scale of the degree marker.

The indicator should be driven from a shaft which, if possible, is unstressed —i.e., rather from the "free" end of the engine than from the extension shaft on the driven machine or dynamometer. It is also desirable to phase the indicator by determining T.D.C. on the actual cylinder to be indicated, as there may be angular errors between the throws of a multi-cylinder shaft.

The actual determination of dead center is clearly the crux of the matter. If this is to be done by measuring the "stationary point," then it is essential, first, to ensure that the bearing clearances are taken up. This may be done by applying a considerable downward force to the piston. The dial indicator used must be sensitive to 0.0001 in. with a wide scale, as the piston movement may, be as small as 0.00016 in. per inch of crank radius, per degree of crank movement. If considerable care be exercised, this method may be satisfactory, and is, indeed, the only mechanical method available if the cylinder center line is offset from the crank center line. As an alternative, if cylinder and crank are not offset, a better method is to measure the angle at which the piston is at a definite position at about half stroke, using a sensitive dial gauge as before. This is done first with the crank on one side of T.D.C. and then repeated from the same piston position on the other side of T.D.C. Dead center may then be assumed with some accuracy to be half way between the two angular positions recorded.

If the cathode-ray indicator is being employed, it may be possible to establish T.D.C. electronically. If there is no Désax—i.e., if cylinder and crank are on the same line—then determination of B.D.C. is as satisfactory as determination of T.D.C. If, therefore, a pick-up be placed close to the piston skirt on B.D.C., a trace can be recorded on the cathode-ray screen showing the movement of the piston. With a sufficiently small gap and sufficient amplification, a fairly accurate determination should be possible. If the engine is of the Désax type, this cannot be done so simply, as the angular displacement

between T.D.C. and B.D.C. is not 180 deg., and allowance must be made for this fact. Alternatively, if normal properly proportioned indicator gear is fitted, and is free from backlash, the pick-up can be placed to record T.D.C. from this gear with some confidence.

To sum up, the error due to incorrect phasing of the indicator is considerable, and can be greater than errors due to inertia and other faults of the conventional piston indicator. The possibility of incorrect phasing is rendered more likely by the large number of variables involved, but mainly by the difficulty of the actual determination of T.D.C. In view of the accuracy with which it is now possible to obtain pressure-time diagrams, considerably more attention should be paid to the problem of phasing, and in view of the high cost of the indicating equipment, some degree of precision in the phasing gear is justified, even though it may be costly. There appears to be no method of detecting an error as small as 1 deg. by investigation of the diagram itself unless the mechanical efficiency of the engine is already known, so that unless the phasing of the instrument is known to be above reproach, derived diagrams constructed from the time-base diagram should be treated with the utmost reserve.

BOOK REVIEW

"HARDENABILITY AND STEEL SELECTION"

By Crafts & Lamont.

From the "Pitman Metallurgy Series," published by the Pitman Publishing Corporation, 2 W. 45th St., New York 19, N. Y.

Reviewed by Lieutenant R. M. Peterson, U.S.N.

Hardenability refers to the percentage of martensite formed on quenching a particular steel. It has been shown that yield strength, endurance limit, elongation, reduction of area, and resistance to single-blow impact are improved and attain their optimum values if the steel as quenched has a structure consisting almost wholly of martensite; also, steels of the same hardenability, when quenched so that the structure is martensitic and then tempered to the same strength, will have similar mechanical properties over 90% of the time. This means that the quenched structure is the most important variable in securing the desired properties. Therefore, hardenability calculations are useful as a guide to better and more accurate decisions in the selection and heat treatment of carbon and low-alloy steels.

Information on hardenability is available but widely scattered, and the main service of this book is its consolidation of the theories, calculations, properties, and test methods The book summarizes the supported hardenability theories and calculations in a logical and readily readable sequence. The ramifications of the heating of the steel for hardening and subsequent quenching are well covered plus a good treatment of the transformation of austenite. The various hardenability test methods are described enabling a proper selection of the most suitable method. The widely used Jominy hardenability control is completely covered. The importance, effects, and contributing factors in tempering after hardening are brought out. The relationships between mechanical properties and hardenability are discussed fully. Lastly, the factors in the selection of steel are effectively described.

The book is well written and beneficial to metallurgists, materials engineers, and designers in making rational selections and effective heat treatmets of steel.

CHANGES IN MEMBERSHIP

The following changes in membership in the Society have occurred since the publication of the August, 1949, JOURNAL:

NEW MEMBERS

NAVAL

Adair, Jamie, Commander, U.S.N., Apt. K-6, U. S. Naval Academy, Annapolis, Md.

Allen, Charles L. D., Commander, U.S.N., c/o Industrial Manager, U.S.N., 9th Naval District, Great Lakes, Ill.

Arnold, Ernest O., Commander, U.S.N.R., Asst. Planning Officer, Industrial Dept., Naval Station, San Pedro, Calif.
Mail: 442 "I" Ave., Coronado, Calif.

Bennett, Rawson, Captain, U.S.N., U. S. Naval Electronics Laboratory, San Diego 52, Calif.

Bird, Robert A., Lieutenant, U.S.N.,
48 Yeamans Ave., Byrnes Down, Charleston, S. C.

Brinckloe, William Draper, Commander, U.S.N.,
Quarters G, Mare Island Naval Shipyard, Mare Island, Calif.

Brockett, William Alden, Commander, U.S.N.,
U. S. Naval Academy, Annapolis, Md.

Clarke, Russell Bernard, Lieutenant, U.S.N.R., Civilian Industrial and Marine Engineer, Office of Industrial Mgr. U.S.N., 9th Naval District, Engineering Officer, U.S.N.R. Div.
Mail: 7305 32d Ave., Konosha, Wis.

Coleman, Lawrence Wayne, Lieutenant, j.g., U.S.N.,
BOQ, Naval Station, Tongue Point, Astoria, Oregon

Collins, Ralph M., Lieutenant, J.G., U.S.N.
USS *Converse* (ARD 39) c/o FPO, San Francisco, Calif.

Coppala, Joseph Augustus, Commander, U.S.N., Production Dept., Puget Sound Naval Shipyard, Bremerton, Wash.

Cowdrey, Roy Thomas, Rear Admiral, U.S.N.,
Commander, Pearl Harbor Shipyard, Pearl Harbor, T.H.

Curr, Chauncey R., Captain, U.S.N.R., Admn. Asst. to C.O. Naval Station, San Diego, Calif. C.O. Organized Naval Reserve Ship Repair Div. 11
Mail: 3515 37th St., San Diego 5, Calif.

Davis, Ernest Raymond, Lieut. Commander, U.SN.,
P. O. Box 131, Lynn, Mass.

Doheny, John Edward, Lieutenant, j.g., U.S.N.
USS PC 1145, Navy 128, c/o Fleet P.O., San Francisco, Calif.

Dougherty, Joseph J., Jr., Lieutenant, U.S.N.,
Code 647, Bureau of Ships, Navy Dept.

Dunford, James Marshall, Commander, U.S.N., Bureau of Ships, Navy Dept.
Mail: 9504 Murray Lane, Falls Church, Va.

Elflein, Charles F., Lieutenant, j.g., U.S.N.R., Marine Engineer
35 Spring Lane, Levittown, L. I., N. Y.

Fleming, Edward S., Commander, U.S.N.,
47 Newbert Ave., South Weymouth, Mass.

Goldsmith, Edward A., Lieutenant, j.g., U.S.N.R., Mech. Engr.
The Hawaiian Electric Co., Ltd., Honolulu, T.H.
Mail: 213 Kaiulani Ave., Honolulu, 15, T.H.

Howe, Wallace Henry, Commander, U.S.N., Industrial Relations Officer, Code 150, Long Beach Naval Shipyard, Long Beach, Calif.

Iselin, Earl Charles, Jr., Lieutenant, j.g., U.S.N.,
Code 848, Bureau of Ships, Navy Dept.

Jezierski, Walter F., Lieutenant, U.S.N.R., Gibbs & Cox, Inc.,
New York, N. Y.
Mail: 138 Oakland St., Brooklyn 22, N. Y.

Johnson, Henry Joseph, Jr., Lieutenant, U.S.N.,
4819 Kansas Ave., Washington, D. C.

Knerr, Hugh Salisbury, Commander, U.S.N.,
Charleston Naval Shipyard, Naval Base, S. C.

Laessle, Frank Willard, Lieutenant, U.S.N.
12 Birch St., Honoja Village, Annapolis, Md.

Lentz, Mervyn, Lieutenant, j.g., U.S.N.R., Vice President and Secretary, Bresome Dist. Corp. P. O. Box 1643, Hartford, Conn.

Love, Richard Emerson, Ensign, U.S.N.,
200 Park Lane, Douglestown, L. I., N. Y.

Manseau, Bernard Edward, Captain, U.S.N.,
Quarters A, San Francisco Naval Shipyard, San Francisco 24, Calif.

Milligan, John C., Lieutenant, j.g., U.S.N.R., Engineering Liaison, Kollmorgen Optical Co., 8 Franklin Ave., Brooklyn 11, N. Y.

Paseur, John Lork, Lieutenant Commander, U.S.N.,
Apt. 3, 2311 Niskaynna Drive, Schenectady, N. Y.

Payne, Charles N., Lieutenant Commander, U.S.N.,
Quarters O, Norfolk Naval Shipyard, Portsmouth, Va.

Pierson, Robert Proudman, Lieutenant Commander, U.S.N.,
Code 740, Bureau of Ships, Navy Dept.

Reigart, John Moulton, Commander, U.S.N.,
4800 Dalton Road, Chevy Chase 15, Md.

Rogers, Thomas Woodson, Commander, U.S.N.,
Naval Shipyard, Mare Island, Calif.

Rollman, Richard Waldeck, Lieutenant, U.S.N.R., O in C & Asst. Inspector U.S.N., Reserve Training Center, Lorain, Ohio.
Mail: U.S.N. Reserve Training Center, 1840 Cleveland Boulevard, Lorain, Ohio

Sadler, William Carroll, Lieutenant, U.S.N.,
David Taylor Model Basin, Washington 7, D. C.

Schierloh, Richard G., Ensign, U.S.N.R.
Austerlit Road, State Line, Mass.

Scott, Bernard, Lieut., U.S.N.R.,
CO 4, USNVA Center, Bath, N. Y.

Shaw, Milton, Lieutenant, U.S.N.R.,
U.S.N. Engineering Experiment Station, Annapolis, Md.

Smith, John Calvin, Ensign, U.S.N.,
USS LSM 341, c/o Fleet P.O., San Francisco, Calif.

Thompson, Goeffrey, Commander, U.S.N.,
Code 646, Bureau of Ships, Navy Dept.

Thornton, Joseph Harden, Jr., Lieutenant, U.S.N.,
14 Hood St., Newton 58, Mass.

Truex, William Wallace III, Lieutenant, j.g., U.S.N.R.,
Welding Engineer, 1801 First St., Northfield, N. J.

Watt, Richard Morgan, Captain, U.S.N.,
Commander, Boston Naval Shipyard, Boston 29, Mass.

Wigner, Frank A., Lieutenant, U.S.N.,
31 Cedar Ave., Newport News, Va.

Wilkinson, Edwin Richard, Rear Admiral, U.S.N., Ret.,
Sales Engineer, Johns Manville Sales Corp.
Mail: 2208 Briarwood Road, Cleveland Heights 18, Ohio

Worley, Arthur Robinson, Jr., Lieutenant, U.S.N.,
4237 E. Roma, Albuquerque, N. M.

CIVIL

Adams, W.R.F., Dist. Manager, General Cable Co.,
261 Constitution Ave., Washington 1, D. C.

Anderson, Martin, In charge Fittings Sec., Planning Div., Naval Shipyard,
Portsmouth, N. H.
Mail: 8 Raleigh Way, Portsmouth, N. H.

Bayard, Arnold A., President, M. L. Bayard & Co., Inc.,
20th St. & Indiana Ave., Philadelphia 32, Pa.

Beckman, Ernest, Mech. Engr., Pearl Harbor Naval Shipyard,
Mail: 700 19th St., Honolulu 62, T.H.

Blanchard, Clement W., Chf. Planner and Estimator,
Naval Shipyard, Long Beach, Calif.

Cecil, Bentley Michael, Planner and Estimator, Pearl Harbor Naval Shipyard,
Mail: Box 409, Ewa, Oahu, T.H.

London, Alexander Louis, Professor of Mechanical Engineering
Stanford University,
Mail: 504 Quad, Stanford University, Calif.

McIlhenny, William Whiting, Jr., Head Engineer, Pearl Harbor Naval Shipyard.
Mail: P. O. Box 134, Pearl City, Oahu, T.H.

Means, Ralph K., Chief Hull Engineer, Pearl Harbor Naval Shipyard.
Mail: 925 16th St. CHA 3, Honolulu, T.H.

Moynihan, Gerald F., Marine Engr. Pearl Harbor Naval Shipyard.
Mail: 919 14th St., CHA III, Honolulu 18, T.H.

Reichelt, Eric, Planner and Estimator, Refrigeration Specialist,
Naval Station, Long Beach, Calif.
Mail: 625 Obispo Ave., Long Beach, Calif.

Santti, Karl, Marine Engineer, Pearl Harbor Naval Shipyard.
Mail: 803 15th St., CHA 3, Honolulu 18, T.H.

Schneier, Samuel, Mech. Engineer, Pearl Harbor Naval Shipyard.
Mail: 714 19th St., CHA 3, Honolulu, T.H.

Starke, Lee, Naval Archt., San Francisco Naval Shipyard.
Mail: 126 Hilltop Road 19-A, San Francisco 24, Calif.

Trilling, Charles, Naval Archt. San Francisco Naval Shipyard.
Mail: 161 Tara St., San Francisco 18, Cailf.

Whitney, Ralph Horace, Field Engineer in Charge Government Sales
The B. F. Goodrich Co., 1112 19th St., N. W., Washington 6, D. C.

Associate

Burket, John A., Technical Research Supervisor, Ships Parts
Control Center, NSD Mechanicsburgh, Pa.
Mail: 19 S. 24th St., Camp Hill, Pa.

Caldwell, Leo F., Technical Research Supervisor, Ships Parts
Control Center, NSD Mechanicsburg, Pa.
Mail: 380 Oak Hill Drive, Middletown, Pa.

Cowan, Joseph Samuel, Dist. Sales Mgr. National Electric Products Corp.
1105 Investment Building, Washington, D. C.

Crough, James Francis, West Coast Representative, Hydraulic Press Mfg. Co.
Mail: 607 Market St., San Francisco, Calif.

Karacostas, Nich, Jr., Marine Engineer, Todd Shipbuilding & Dry Dock Co.,
Galveston, Texas.
Mail: 4801 Alamo Drive, Galveston, Texas

Manning, John McVeigh, Engineering Dept., Casualty Insurance Co.
Mail: The Employees Group, 603 Hibernia Bank Building
New Orleans, La.

Tepperman, Harry P., President, Atlas Paint & Varnish Co., Irvington, N. J.
Mail: 151 North Wyoming Ave., South Orange, N. J.

Townsend, William, Vice President in Charge Sales, Pennsylvania
Flexible Metallic Tubing Co., 72d St. & Powers Lane,
Philadelphia 42, Pa.

Ward, F. Hugh, Fairbanks, Morse Co.,
1427 Eye St., N. W., Washington, D. C.

Wilson, Alan Christopher Wyndham, Lieutenant Commander (E) R.N.
c/o AEO John Brown, Ltd., Clyde Bank, Glasgow, Scotland, U.K.

Transferred Associate To Naval

Smith, John S., Commander, U.S.N.R., Philadelphia Naval Shipyard.
Mail: 937 Spruce St., Philadelphia, Pa.

MEMBER'S ADDRESSES

All members are urged to check the address under which they received the last mail from the Society and to drop a penny post card in the mail to us advising of any change in address which is in order.

ASSOCIATION NOTES

Original Articles

The editor of the JOURNAL is most anxious to obtain manuscripts of original articles on subjects of interest to naval engineers. Any manuscript accepted for publication becomes the property of the Society which copyrights it upon publication. Authors are paid from $50.00 to $150.00 depending upon length, interest and professional value.

The rules for manuscripts are as simple as we can make them.

1. They must be legible (typewritten, double-spaced preferred) since no proof is submitted to authors for correction prior to printing.

2. Single copy only is required.

3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.

4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.

5. Photographs may be negatives, but glossy prints are acceptable.

6. Include on a separate page a short biographical sketch(es) of the author(s). 50 to 100 words for each author is desired.

Manuscripts should be mailed addressed to:

Secretary-Treasurer
American Society of Naval Engineers
Bureau of Ships, Navy Department
Washington 25, D. C.

Manuscripts accepted will not be returned unless specifically requested by the author. If returned, they will be in the condition which has resulted from the work of the printer and the engraver. Immediately following publication, the author is furnished 10 reprint copies of his article free of charge. Additional copies may be purchased from the Society if the request is received 30 days prior to the publication date which is the 25th of the issue month. Estimate of cost of additional reprints, which will vary with the nature of the article and the number of copies ordered, will be furnished on request as soon as possible after the article is set up.

Manuscripts not accepted will be returned, postpaid, by the Society.

Manuscripts which are accepted will be published in the earliest JOURNAL which has not yet been closed (60 days before publication) and for which insufficient material is already on hand.

SUBJECT MATTER AND AUTHORS

To assist the editor in programming future issues, the help of all members is solicited. To make it easy, the last page in this issue is readily detachable as you will find. This page has blanks for two entries.

(*a*) What subject would you, as a member, like to see covered by an article in the JOURNAL.

and

(*b*) Who do you consider best qualified to prepare such an article authoritatively, and what is his address. (if you know).

Any of these forms which are filled in and mailed to the Society will be received with thanks and the editor will follow up to get the suggested articles prepared.

PHOTOGRAPHS

Photographs of current or historical interest to readers of the JOURNAL are desired. Any which are accepted by the Society will be purchased by the Society at a standard price of $5.00 each. Such purchase *will not* include any copyright by the Society, but the contributor must hold the Society free from any charge of violation of any previous copyright.

NOTICE OF DEATHS

The Society has no satisfactory machinery for obtaining notice of deaths of members. It is particularly desired that we receive such notice upon the death of any past officer, past member of the Council or member of more than twenty years' standing with photographs and short obituaries. It will be appreciated greatly if any member who learns of the death of a member will advise the Secretary-Treasurer.

SOCIETY LAPEL BUTTON

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine dignified insignia. It is one-half inch in diameter.

The oak leaves and lettering are red on a gold back-ground.

It is available to all members at fifty cents (50c) each.

Annual Meeting

The annual meeting of the Society was held in Washington, D. C. on Tuesday, 4 October 1949. A considerably larger number than the required quorum attended.

The following report from the nominating committee was received and accepted without change:

"115 Hesketh St.,
Chevy Chase-15-Md.,
September 9, 1949

Mr. President:

Your committee appointed by your letter of 24 August, 1949, has met in compliance with your request and, adhering to the applicable requirements of the Constitution of the Society, formerly presents the following as nominees for Officers of the American Society of Naval Engineers for the calendar year 1950:

For President:
Rear Admiral Frederick E. Haeberle, U. S. Navy

For Secretary-Treasurer:
Captain James E. Hamilton, U. S. Navy
Captain William A. Dolan, U. S. Navy

For Member of Council:
Regular Navy:
Rear Admiral Theodore C. Lonnquest, U. S. Navy
Rear Admiral Louis Dreller, U. S. Navy
Captain Charles M. Tooke, U. S. Navy
Commander Ivan Monk, U. S. Navy
Coast Guard:
Captain Robert A. Smyth, U. S. Coast Guard
Commander Richard D. Schmidtman, U. S. Coast Guard
Naval Reserve:
Captain Walter M. Tann, U. S. Naval Reserve
Commander Frederick Wiesner, U. S. Naval Reserve
Civilian:
Mr. John H. Schombert, Bureau of Ships, Navy Department
Mr. Francis H. Engel, Radio Corportation of America

Very truly yours,

Harvey F. Johnson,
Rear Admiral, U. S. Coast Guard (Ret)

Rear Admiral T. A. Solberg, U. S. Navy
President, American Society of Naval Engineers
Office Research and Development
Department of the Navy
Washington, D. C."

The President reported the receipt of the report of the auditing committee which is as follows:

24 August 1949

"Rear Admiral T. A. Solberg
Chief of Naval Research
Washington 25, D. C.

Dear Admiral Solberg:

The committee which you as President of the American Society of Naval Engineers appointed to audit the accounts of the Secretary-Treasurer of the Society for the calendar year 1948 met at the home of Mr. A. G. Fessenden, Clerk of the Society, on 20 July 1949. The entire board was present, consisting of myself as chairman and Captain W. B. Armstrong, U.S.N.R., and Mr. James W. Jenkins (vice Mr. Charles G. Cooper) as members, in accordance with your letters of 8 June and 20 July 1949. The Secretary-Treasurer Captain James E. Hamilton was also present.

The committee determined that the accounts of the Society for the year 1948 are in order and have been carefully kept. The committee did not conduct an audit akin to a certified public accountant's audit, but satisfied itself to the fullest extent possible without so doing that the records were complete and accurate. A statement of income and expenditures and a balance statement is appended, signed by the members of the committee.

As chairman of the committee I sighted the Society's securities, a list of which is appended. The Secretary was also present at the sighting.

The auditing committee discovered in conducting its audit that there now exists a large number of members delinquent in payment of their dues. The Secretary is, however, aware of this fact and is taking the best action indicated in each case to reduce these accounts receivable.

The committee discussed informally with the Secretary the advisability of raising the Society dues in order to obviate possible losses in future years of similar magnitude to the $10,352 loss during 1948. The committee does not desire, however, to make specific recommendation that the dues be increased.

The committee discussed the advisability of the Society's requiring a CPA audit of the accounts. The consensus was that the cost of conducting such an audit would be excessive and out of all proportion to the need. The books are considered to be entirely in order and hence no real need for an accountant's audit is believed to exist.

Frank C. Jones"

On a motion from the floor which was carried, it was decided to poll the membership on a change in the By-laws to provide for life membership. This will appear as proposition Number 3 on the ballots which are in members hands. If approved this change will be effective in 4 January, 1950. Because of the need for detailed consideration, the proposed change will empower the Council to decide whether life membership will be offered at a flat rate or at a life-expectancy rate and what the rate will be.

The other two proposed changes which are included on the ballot are discussed under Secretary's Notes.

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

FINANCIAL STATEMENTS, 1948

TRIAL BALANCE

Cash		$ 3855.55	
Accounts Receivable:			
Advertisements	$ 1915.70		
Dues	3503.85		
Sales	73.75		
Subscriptions	1942.80	7436.10	
Investments:			
U. S. Defense Bonds, Series G	$71000.00		
Washington Gas Light Co.	997.50	71997.50	
Furniture		118.00	
Income (Publication):			
Advertisements	$ 6187.50		
Dues	14562.50		
Sales, General	174.52		
Sales (Buttons)	28.50		
Subscriptions	8394.15		$29347.17
Expenditures (Publication):			
Printing	$24299.09		
Engraving	2394.70		
Manuscript	2365.00		
Manuscript in Advance (for 1949)	775.00		
Postage	355.53		
Commission	101.70		
Exchange	.65	30291.67	
Interest on Investments			2073.60
Banquet, 1948		2700.21	
Scholarship, Webb Institute		2000.00	
General Expense		1112.71	
Salaries		4080.00	
Current Profit and Loss		1588.50	
Dues Paid in Advance			422.50
Advertisements Paid in Advance			285.00
Subscriptions Paid in Advance			4045.20
Capital Account			89006.77
		$125180.24	$125180.24

Statement of Income and Expenditures

Expenditures

Publication:			
Printing		$24299.09	
Engraving		2394.70	
Manuscript		2365.00	
Manuscript in Advance		775.00	
Postage		355.53	
Commission		101.70	
Exchange		.65	$30291.67
Salaries			4080.00
Scholarship			2000.00
General Expense			1112.71
Current Profit and Loss			1588.50
Banquet, 1948			2700.21
			$41773.09

Income

Publication:			
Dues	$14562.50		
Advertisements	6187.50		
Sales, General	174.52		
Sales, Lapel Buttons	28.50		
Subscriptions	8394.15	$29347.17	
Interest on Investments		2073.60	31420.77
NET LOSS			$10352.32

BALANCE STATEMENT

Total Assets January 1, 1948.....			$89006.77
Assets December 31, 1948:			
Cash		$ 3855.55	
Accounts Receivable:			
Advertisements.....	$ 1915.70		
Dues.....	3503.85		
Sales	73.75		
Subscriptions	1942.80	7436.10	
Investments (Bonds)			
U. S. Denfense, Series G.....	$71000.00		
Washington Gas Light Co.....	997.50	71997.50	
Furniture.....		118.00	
		$83407.15	
Liabilities (Accounting Only)			
Dues Paid in Advance.....	$ 422.50		
Advertisements Paid in Advance....	285.00		
Subscriptions Paid in Advance.....	4045.20	4752.70	
Total Net Assets.....			78654.45
NET LOSS.....			$10352.32

Respectfully submitted

J. E. Hamilton, Secretary-Treasurer

Audited and Found Correct:

Frank C. Jones
W. B. Armstrong } Audit Committee
James W. Jenkins

For
Gen
Driv
abili
pact
more
by su
ing
Gen
one

CLE

Diesel-Electric

saves space for paying cargo

For cargo vessels and tankers, General Motors Diesel-Electric Drive provides ease of control, maneuverability, dependability. Light-weight, compact units insure low-cost operation and more space for paying cargo. Then, too, by supplying complete power plant, including propulsion and auxiliary equipment, General Motors centers responsibility in one company.

Outstanding Diesel Developments

1915—the first V-type 12-cylinder Diesel engine was built by the Winton Gas Engine and Manufacturing Company, forerunner of the Cleveland Diesel Engine Division of General Motors

Leader in Diesel engineering development for 37 years

CLEVELAND DIESEL ENGINE DIVISION

CLEVELAND 11, OHIO

GENERAL MOTORS

GM GENERAL MOTORS DIESEL POWER

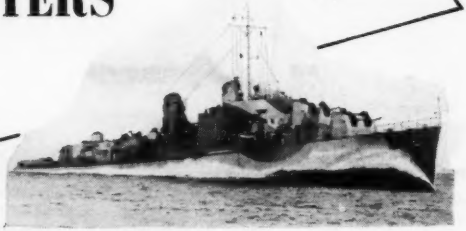
ENGINES FROM 150 TO 2000 H.P.

For

THE WORLD'S BEST
NAVY

THE WORLD'S BEST
DESTROYERS

BIW



BATH IRON WORKS CORPORATION BATH • MAINE

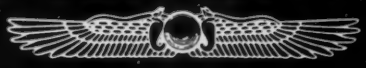
RCA . . .

the leading manufacturer of
SHORAN . . . LORAN . . . TELERAN . . .
RADAR . . . RADAR ALTIMETERS . . .
SONAR . . . BATTLE ANNOUNCE and
RADIO COMMUNICATIONS EQUIPMENT

GOVERNMENT EQUIPMENT SECTION
RADIO CORPORATION of AMERICA
ENGINEERING PRODUCTS DEPARTMENT, CAMDEN, N.J.

There's more worth in

WORTHINGTON



EQUIPMENT FOR THE MARINE FIELD

For craft of every size and type

CENTRIFUGAL PUMPS
STEAM PUMPS
POWER PUMPS
STEAM CONDENSERS
STEAM-JET EJECTORS
FEEDWATER HEATERS
AIR COMPRESSORS
DIESEL ENGINES
STEAM TURBINES
SPEED-CHANGE GEARS

Worthington engineers from the rough layout to the ships at sea

M9-1

WORTHINGTON PUMP AND MACHINERY CORPORATION
HARRISON, NEW JERSEY

Model 37: 500 to 2125 horsepower for direct drive marine service.
Model 32: Horsepower from 120 to 450. For slow-speed heavy-duty service.
Model 42: 60 and 90 horsepower at 450 r.p.m.
Model 31: Horsepower from 175 to 500; with 2 to 1 reduction gears optional for marine service.
Model 38 Opposed-Piston Engine: Horsepower from 960 to 1920 with 2 to 1 reduction gear for marine service.
Model 33 Stationary Engine: 500 to 2000 hp. Diesel, 1000 to 2000 hp. Dual Fuel.
Model 38 Opposed-Piston Engine: 960 to 1920 horsepower at 720 r.p.m.
Model 31: 2100 to 3500 horsepower diesel or dual fuel engine for heavy-duty stationary service.

When it comes to Diesel Power...

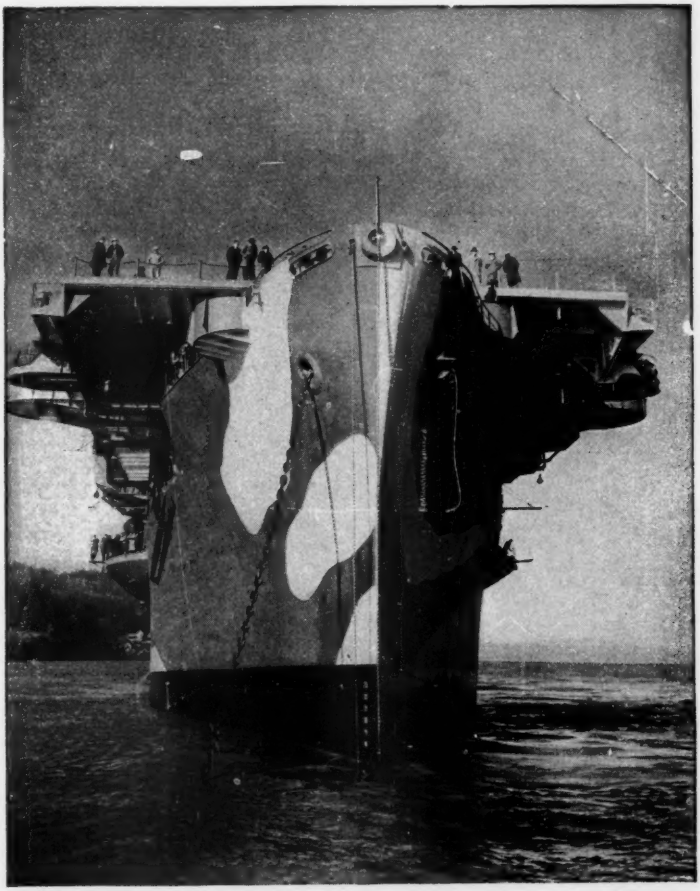
From 3.5 hp. to 3500 hp.

Low-cost, efficient power for all marine services modern, dependable power for newest, fastest road locomotives. economical power for largest to smallest municipal and industrial plants Fairbanks-Morse is the proved source for the full range of diesel applications. For skilled assistance and impartial recommendation for the diesel for your specific service, write Fairbanks, Morse & Co., Chicago 5, Ill.

FAIRBANKS-MORSE

A name worth remembering

DIESEL LOCOMOTIVES • DIESEL ENGINES • PUMPS • SCALES
MOTORS • GENERATORS • STOKERS • RAILROAD MOTOR CARS and STANDPIPES • FARM EQUIPMENT • MAGNETOS



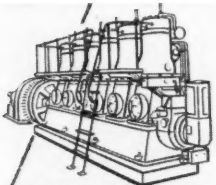
CONSTRUCTORS OF MARINE EQUIPMENT FOR U. S. NAVAL VESSELS SINCE 1891.

Steam Generators	Condensers	Distillers
Superheaters	Economizers	Air Ejectors

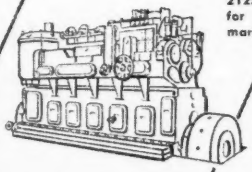
Vacuum Refrigeration Air-Conditioning Units

FOSTER WHEELER CORPORATION, 165 Broadway, New York 6, N. Y

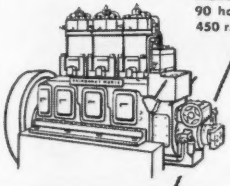
FOSTER WHEELER



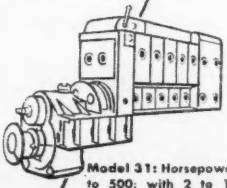
Model 32: Horsepower from 120 to 450. For slow-speed heavy-duty service.



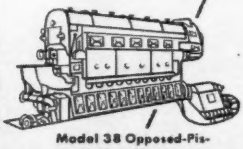
Model 37: 500 to 2125 horsepower for direct drive marine service.



Model 42: 60 and 90 horsepower at 450 r.p.m.

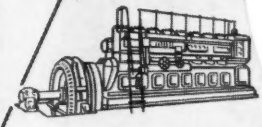


Model 31: Horsepower from 175 to 500; with 2 to 1 reduction gears optional for marine service.



Model 38 Opposed-Piston Engine: Horsepower from 960 to 1920 with 2 to 1 reduction gear for marine service.

Model 33 Stationary Engine: 500 to 2000 hp. Diesel, 1000 to 2000 hp. Dual Fuel.



When it comes to Diesel Power...

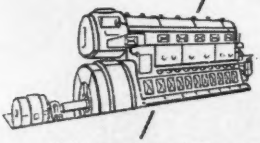
From 3.5 hp. to 3500 hp.

Low-cost, efficient power for all marine services modern, dependable power for newest, fastest road locomotives . economical power for largest to smallest municipal and industrial plants Fairbanks-Morse is the proved source for the full range of diesel applications. For skilled assistance and impartial recommendation for the diesel for your specific service, write Fairbanks, Morse & Co., Chicago 5, Ill.

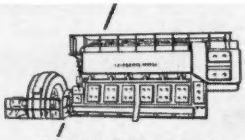
FAIRBANKS-MORSE

A name worth remembering

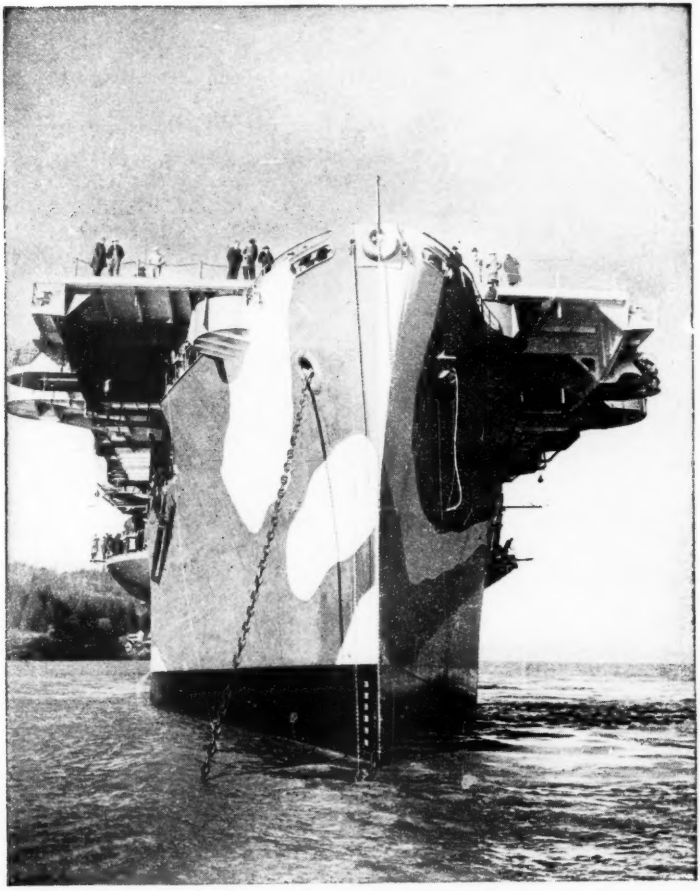
DIESEL LOCOMOTIVES • DIESEL ENGINES • PUMPS • SCALES
MOTORS • GENERATORS • STOKERS • RAILROAD MOTOR CARS and STANDPIPES • FARM EQUIPMENT • MAGNETOS



Model 38 Opposed-Piston Engine: 960 to 1920 horsepower at 720 r.p.m.



Model 31: 2100 to 3500 horsepower diesel or dual fuel engine for heavy-duty stationary service.



CONSTRUCTORS OF MARINE EQUIPMENT FOR U. S. NAVAL VESSELS SINCE 1891.

Steam Generators	Condensers	Distillers
Superheaters	Economizers	Air Ejectors

Vacuum Refrigeration Air-Conditioning Units

FOSTER WHEELER CORPORATION, 165 Broadway, New York 6, N. Y

FOSTER WHEELER

For the Merchant Marine and the Navy

CAMERON PUMPS . . . Circulating, Condensate, Boiler Feed, Cargo, Bilge, Ballast, Fire, Butterworth, etc. A full line designed especially for Marine Service.

STEAM CONDENSERS . . . Space saving models in the new Rectangular Design to suit all conditions.

STEAM-JET AIR EJECTORS . . . Models designed to fit the condensers they serve.

AIR TOOLS . . . Chippers, Scalers, Hammers, Grinders, Impact Wrenches, etc. A complete line of Air Tools including Air-Starting Motors.

AIR COMPRESSORS . . . All sizes and types for diesel-starting and general service.

DIESEL ENGINES . . . 195 HP to 900 HP. For heavy-duty service at 720 and 1000 rpm.

Branches everywhere . . . Write for individual Bulletins.

Ingersoll-Rand

11 BROADWAY, NEW YORK 4, N. Y.

465-14

PROVEN IN THE SERVICE

For 50 years, Cutler-Hammer, **Pioneer Electrical Manufacturer,** has furnished dependable control to all departments of the United States government. Built to specifications . . . backed by an outstanding record of performance.

CONTROL APPARATUS FOR ALL MARINE USES

Motor Control for Every Service, Ventilating Fans, Pumps, Cargo Winches, Capstans, Windlasses, Laundry Machines, etc.

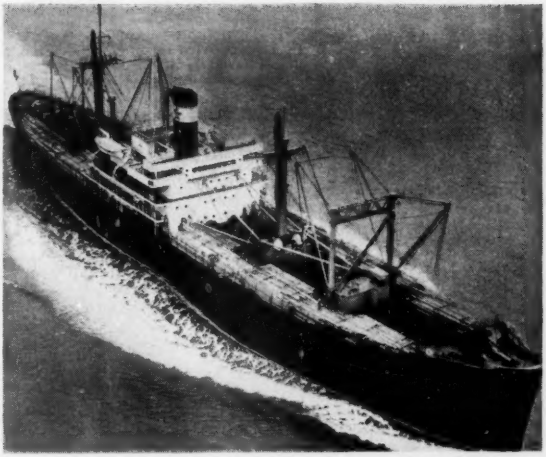
Magnetic Brakes,
Motor Operators for Valves,
Limit Switches,
Solenoids, Rheostats,

CUTLER-HAMMER
MOTOR CONTROL
C-H

Pressure Regulators,
Magnetic Clutches,
Watertight Door Control,
Pushbuttons

CUTLER-HAMMER, Inc., 1354 St. Paul Avenue, MILWAUKEE 1, WIS.

TROUBLE-FREE OPERATION FOR POPE & TALBOT



Pope & Talbot's executive vice-president Charles L. Wheeler enthusiastically says, "Not a penny has been spent on repair work for shoreside maintenance on the General Electric equipment in our ships."

Shown above is the P & T *Seafarer*—G.E. equipped from the main propulsion drive to the radar unit, one of six Pope & Talbot C-3's driven by G.E. 8500-hp geared-turbine propulsion units. Five of these are also equipped with G.E. 250-kw turbine-generator sets.

By the end of 1949 these P & T ships will have logged over 850,000 nautical miles since the inauguration of the Pacific Argentine Brazil Line three years ago. During that time their G-E equipment has performed reliably and economically without breakdowns or failures.

For dependable electrical or propulsion service of this type see your nearest G.E. representative. ***Apparatus Department, General Electric Company, Schenectady 5, N. Y.***

GENERAL ELECTRIC

200-72D

Photograph courtesy of Cummins Engine Company, Inc., Columbus, Indiana

Tire-shaped rubber packing rings for cylinder liners in Cummins diesel engines are small but important. They provide a seal between oil and water — a seal that must be perfect whether the engine is cold or operating at high temperatures. Moreover, these rubber rings must stand up for at least the equivalent of 100,000 miles of operation.

These severe operating requirements presented a rubber problem with exacting specifications. Resistance to sustained heat. Controlled swell in oil. Exceptional compression quality. Precision tolerances.

The successful solution of this problem is typical of the "service in rubber" offered by Continental.

When *you* need rubber parts, why not enlist the assistance of specialists?

CONTINENTAL
RUBBER WORKS
ERIE • PENNSYLVANIA • U S A

U. S. NAVAL INSTITUTE

FOUNDED IN 1873

"FOR THE ADVANCEMENT OF PROFESSIONAL, LITERARY, AND SCIENTIFIC KNOWLEDGE IN THE NAVY"

U. S. NAVAL INSTITUTE PROCEEDINGS

PUBLISHED MONTHLY, ILLUSTRATED EXTENSIVELY, FOR OVER SEVENTY YEARS HAS BEEN THE NAVY'S FORUM.

MEMBERS OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS

Should read the PROCEEDINGS for pleasure and profit. The issues contain anecdotes and reminiscences, incidents from history and essays on topics of naval interest, technical articles and treatises on naval development and progress, book reviews and discussions, and international and professional notes. Membership dues (including PROCEEDINGS), $2.00 a year. Subscription rate, $4.00 a year. (Foreign postage, $1.00 extra.) Single copies 50 cents (except some scarce issues).

APPLICATION FOR MEMBERSHIP

Date .....

SECRETARY–TREASURER
U. S. NAVAL INSTITUTE
ANNAPOLIS, MARYLAND

I hereby apply for membership in the U. S. Naval Institute and enclose $2.00 in payment of dues for the first year to begin with the .....issue of the PROCEEDING (the monthly magazine of the U. S. Naval Institute).

I am interested in the objects and purposes of the Institute, namely, the advancement of professional, literary, and scientific knowledge in the Navy. I am a citizen of the United States and understand that members are liable for dues until the date of receipt of their written resignations.

Name .....

Address .....

.....

SHIPBOARD CABLES
(a) Single conductor rubber insulated cable
(b) Multi-conductor Navy Type power cable
(c) Varnished cambric marine cable with basketweave armor
LOW COSTS ON THE HIGH SEAS
LOW COSTS IN YARD USE
SHIPYARD CABLES
(d) Okolite-Okoprene - up to 5000 volts
(e) Okolite-Okoprene - high voltage
(f) Varnished cambric braided

Long-lived Okonite cables insure freedom from service interruptions, and because of this consistent failure-free performance, protect against the high installation costs of today.

A wide variety of Okonite wires and cables is at your service for shipboard and shore installations. They include the six cables shown here and a number of other widely-used marine types. For information on all Okonite cables, including those that meet U. S. Navy and A.I.E.E. specifications, please address The Okonite Company, Passaic, New Jersey.

OKONITE OKONITE SINCE 1878 **insulated wires and cables**

4974

Worldwide Experience

in Communications Research and Manufacture

— in the Service of America

While I. T. & T.'s associate companies abroad are contributing to the rehabilitation and expansion of communications in nations ravaged by the war, the technical skills of the System affiliates in this country are devoted largely to the service of the United States. Its American research unit, Federal Telecommunication Laboratories—with its unique experimental tower —and the factories of the Federal Telephone and Radio Corporation are united in a productive partnership dedicated to the achievement of better communications for the nation.

INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION
67 Broad Street, New York 4, N. Y.

U. S. Manufacturing Subsidiary—Federal Telephone and Radio Corporation
U. S. Research Unit—Federal Telecommunication Laboratories

KEARFOTT

An organization that has supplied windows for the finest vessels afloat.

♦ ♦

Windows designed to meet the severe test of marine service.

KEARFOTT ENGINEERING CO.

117 Liberty Street **New York 6, N. Y.**

The TERRY TURBINE

For driving Generators, Boiler Feed Pumps, Fuel Oil Pumps, etc., Terry Marine Turbines offer many advantages.

They are backed by over 40 years of experience in the Marine Field on both Commercial and Naval Vessels.

They are Dependable, Compact, Efficient, and are especially designed for use aboard ship. They are built in the Terry Solid Wheel design as well as in the axial flow single stage and multi-stage types. Sizes 5 H. P. to 2000 H. P.

Complete details on any turbine application will be gladly furnished.

THE TERRY STEAM TURBINE COMPANY

TERRY SQUARE HARTFORD, CONN T-1155

KINGSBURY
THRUST BEARINGS

Through two World Wars, Kingsburys have been preferred for difficult conditions of load or speed, and for applications demanding maximum dependability with minimum care and maintenance.

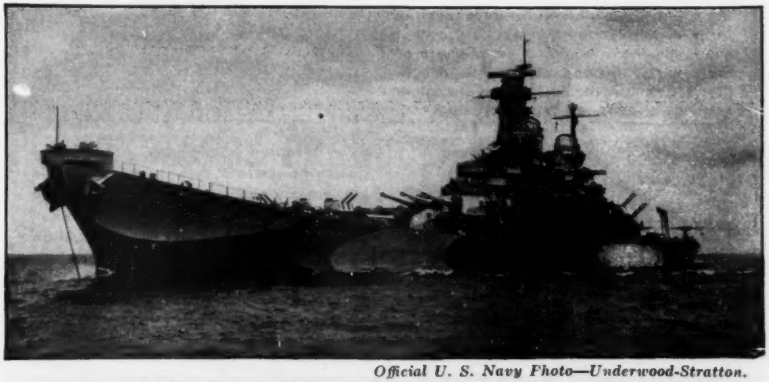
Due to the Kingsbury Principle of tilting "shoes" and wedge-shaped oil films, there is no metallic contact while running, and the working surfaces have indefinite life.

KINGSBURY MACHINE WORKS, INC.

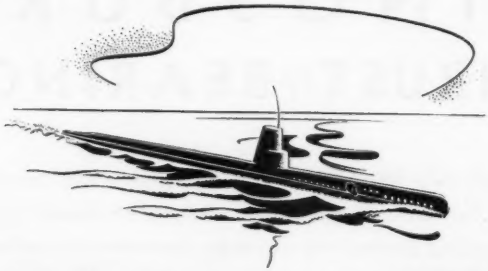
PHILADELPHIA 24, PA.

KINGSBURY

U. S. S. "MISSOURI"
Each battleship of this class has 36 Kingsbury Bearings, including four, size 49 in., on propeller shafts.



Official U. S. Navy Photo—Underwood-Stratton.



OUR SINEWS ARE STILL "IN CONDITION"

AS the principal builder of submarines for the U. S. Navy since 1900, we are wholly conscious of a special responsibility . . . the responsibility to maintain all our facilities and personnel in a state of preparedness for the security of our country.

Since the end of World War II we have kept our sinews exercised, our minds alert. Following the recent completion of the "Guppy" project of submarine conversion and modernization, we are now proceeding under Navy contract to design and build four new subs. At the same time we are continuing, in collaboration with the Navy, a vigorous program of submarine research and development.

ELECTRIC BOAT COMPANY

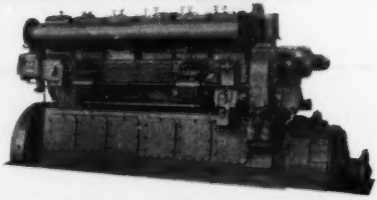
Groton, Connecticut

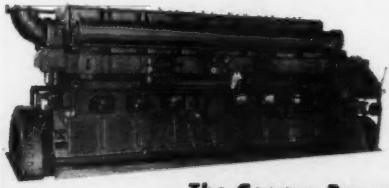
New York Office
445 Park Avenue, New York 22, N. Y.

Other Plants
Bayonne, N. J. Montreal, Canada

WHEREVER THERE'S A COOPER-BESSEMER THERE'S RELIABLE POWER!

Navy and Coast Guard men who have had experience with C-B Diesels, who have depended upon them in action, know that these fine engines stand for dependability in its broadest sense. Perhaps they do not know that the outstanding performance of every modern Cooper-Bessemer is due in part to a century-old background of engine-building experience. This, combined with





truly advanced engineering, has enabled Cooper-Bessemer Diesels to do a notable job in Navy and Coast Guard vessels from the biggest combat ships to relatively small patrol boats. Yes, you can always count on Cooper-Bessemers for Diesel performance at its finest.

The Cooper-Bessemer Corporation

MOUNT VERNON, OHIO — GROVE CITY, PENNA.

BUILDERS OF FINE ENGINES FOR 115 YEARS

The vast experience of Ward Leonard includes the entire period of the application of electricity. Every item in the line of Ward Leonard controls is a product of sound engineering, practical designing and careful manufacture . . . each planned to meet a specific set of conditions . . .

Resistors . . . Rheostats . . . Relays . . . Contactors Motor Starters . . . Controllers . . . Speed Regulators . . . Automatic Voltage Regulators . . . Dimmers.

ELECTRIC CONTROL DEVICES SINCE 1892

WARD LEONARD ELECTRIC CO.

MOUNT VERNON NEW YORK

COLLINS RADIO COMPANY

CEDAR RAPIDS, IOWA

11 West 42nd Street
New York 18, N. Y.

458 South Spring Street
Los Angeles 13, California

Designers and manufacturers of radio communication and navigation equipment for the Armed Services.

ROCKBESTOS PRODUCTS CORPORATION

Manufacturers of flameproof insulated wires and cables, heat-resisting flexible cords, and armored flameproof and waterproof shipboard cable.

Main Office and Works
NEW HAVEN, CONNECTICUT

New York Cleveland Detroit Chicago
Pittsburgh St. Louis Los Angeles Oakland, Calif.

Griscom-Russell

Distilling Plants
Feed Water Heaters
Oil Coolers — Jacket Water Coolers
G-Fin Fuel Oil Heaters

Bulletins on Request

THE GRISCOM-RUSSELL CO.

285 MADISON AVENUE, NEW YORK

GIBBS & COX, INC.

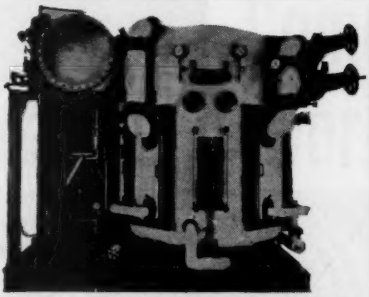
NAVAL ARCHITECTS AND MARINE ENGINEERS

ONE BROADWAY - 21 WEST STREET

NEW YORK, NEW YORK

WELDED EVERDUR SHELLS

Assure High Strength and Corrosion Resistance in Paracoil Seawater Still



Completely self-contained Paracoil Low Pressure Distilling Plant by the Davis Engineering Corporation for C-3 freighters.

The new Paracoil Low Pressure (Vacuum) Double-Effect Salt Water Distilling Plant fabricated by the Davis Engineering Corporation of Elizabeth, N.J. for Maritime Commission Design C3-S-A-5 cargo vessels, is designed to produce 12,000 gallons of distilled water in 24 hours with no more than 0.25 grams of chlorine per gallon of distillate.

Two-stage evaporation is accomplished in the welded Everdur* shell, divided vertically by a double-walled Everdur partition. Condenser tubes are of 70-30 Cupro-Nickel and the helical evaporator heating coils are of copper. For detailed information on Everdur Copper-Silicon Alloys, as well as standard and special alloys for condenser tubes and plates, write The American Brass Company. 49126B

*Reg. U. S. Pat. Off.

ANACONDA
Everdur
COPPER-SILICON ALLOYS
THE AMERICAN BRASS COMPANY
General Offices: Waterbury 88, Conn.
Subsidiary of Anaconda Copper Mining Co.
In Canada:
ANACONDA AMERICAN BRASS LTD.
New Toronto, Ont.

THE BERWIND-WHITE COAL MINING CO.

1 BROADWAY, NEW YORK 4, N. Y.

PROPRIETORS, MINERS AND SHIPPERS OF

BERWIND'S EUREKA

BERWIND'S STANDARD NEW RIVER and

BERWIND'S STANDARD POCAHONTAS

SMOKELESS STEAM COALS

ALSO

BERWIND'S STANDARD ELKHORN

BETHLEHEM STEEL COMPANY

Shipbuilding Division

SHIPBUILDERS • SHIP REPAIRERS

Naval Architects and Marine Engineers

General Offices: 25 Broadway, New York 4, N. Y.

SHIPBUILDING YARDS

QUINCY YARD
Quincy, Mass.

STATEN ISLAND YARD
Staten Island, N. Y.

BETHLEHEM-SPARROWS POINT SHIPYARD, INC.
Sparrows Point, Md.

BEAUMONT YARD
Beaumont, Texas

SAN FRANCISCO YARD
San Francisco, Calif.

SAN PEDRO YARD
Terminal Island, Calif.

SHIP REPAIR YARDS

BOSTON HARBOR
Atlantic Yard
Simpson Yard

NEW YORK HARBOR
Brooklyn 27th Street Yard
Brooklyn 56th Street Yard
Hoboken Yard
Staten Island Yard

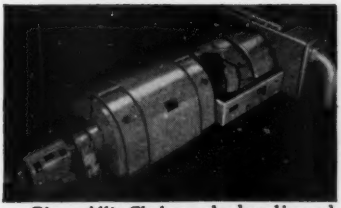
BALTIMORE HARBOR
Baltimore Yard

GULF COAST
Beaumont Yard
(Beaumont, Texas)

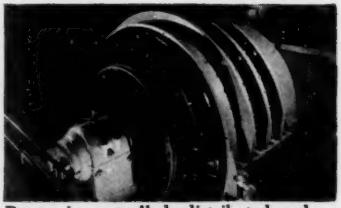
SAN FRANCISCO HARBOR
San Francisco Yard
Alameda Yard

SAN PEDRO HARBOR
(Port of Los Angeles)
San Pedro Yard

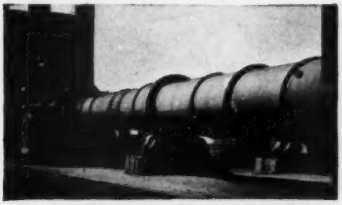
Your Good Living Comes From This Hidden World



Giant Allis-Chalmers hydraulic and steam turbines with their generators and controls provide dependable, low cost light and power for your home, your job, your recreation.



Power is controlled, distributed and utilized through Allis-Chalmers transformers, switchgear, regulators and motors . . . turning raw electric power into useful energy.



Allis-Chalmers makes major industrial equipment for *every* basic industry . . . mining, cement and rock products, food, chemical, pulp and paper, textile, petroleum, steel; pumps and V-belt drives for all industry.

Allis-Chalmers makes tractors for agricultural and industrial uses plus a complete line of implements and accessories. All these varied lines mean better living for all Americans . . . better living for you.

Nearly every one of the things that you use, wear or eat is helped somewhere along its road to you by one of Allis-Chalmers many products. For Allis-Chalmers makes a wider range of major industrial products than any other company . . . products in industry's "hidden world" of machinery that serve you and every American.

MILWAUKEE 1, WISCONSIN

ALLIS-CHALMERS

A-2895

One of the Big 3 in Electric Power Equipment . . .
Biggest of All in Range of Industrial Products

TEAR OUT, FILL IN THE TWO BLANK SPACES
SIGN AND MAIL TO:

Secretary-Treasurer
The American Society of Naval Engineers, Inc.
Bureau of Ships, Navy Department,
Washington 25, D. C.

I would like to see an article in the JOURNAL of the following subject:

.....

.....

I suggest that.....

.....could prepare an authoritative article on the above subject.

.....
Member

QUALIFICATION FOR MEMBERSHIP

Commissioned and ex-commissioned officers of the regular Navy, Marine Corps and Coast Guard of the United States; warrant and ex-warrant officers of the regular Navy, Coast Guard and Marine Corps of the United States; reserve commissioned and warrant officers of the Navy, Coast Guard and Marine Corps of the United States shall be eligible as Naval Members. Persons eligible as naval members shall be admitted upon application and payment of annual dues.

Persons in civil life whose knowledge of engineering is such that they can cooperate with Naval engineers in the promotion of professional knowledge may be eligible as civil members. They shall have been in the active practice of an engineering profession for at least eight years and in responsible charge of important work for five years, and shall be qualified to design as well as to direct engineering work. Fulfilling the duties of a professor of engineering who is in charge of a department in a college or school of accepted standing shall be taken as an equivalent to an equal number of years of active practice. Graduation from a school of engineering of recognized standing shall be considered as equivalent to two years of active practice. Persons eligible as civil members may be admitted upon application and payment of annual dues, provided that the application is accompanied by the recommendation of two members and provided that the application shall receive the approval of a majority of the Council.

Persons in civil life who are not eligible for civil membership, but who are especially interested in naval matters or the merchant marine may be eligible as associate members. Commissioned officers of the United States Army and of foreign military and naval services may be eligible as associate members. Persons eligible to associate membership may be admitted upon application and payment of annual dues, provided the application have the recommendation of a member and provided the application shall receive the approval of a majority of the Council, except that in the case of commissioned officers of the United States Army and of foreign naval and military services, the recommendation of a member will not be required.

Associate members shall be entitled to all the privileges of other members except voting and holding office.

APPLICATION FOR MEMBERSHIP IN THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

Date_____

I hereby make application for membership* in the American Society of Naval Engineers and submit the following information:

For Naval Membership

(First) (Middle) (Last)

Name _____

Rank_____ File No._____

Business connection and position, if any_____

For Civil Membership

(First) (Middle) (Last)

Name _____

Years in engineering work_____

Years in responsible charge of important work_____

Present business connection and position_____

Recommended by (two members)_____

_____

For Associate Membership

(First) (Middle) (Last)

Name _____

Rank, if Commissioned Officer of U. S. Army or of foreign military or Naval service_____

Business connection and position_____

Recommended by (one member)_____

_____

Signature of Applicant

Address for Journal and Mail

_____

_____

MAIL TO SECRETARY-TREASURER
THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.
BUREAU OF SHIPS, NAVY DEPT., WASHINGTON, D. C.

* See reverse side for required qualifications for various classes of membership.

SECRETARIES OF THE SOCIETY

Current:

Captain J. E. HAMILTON, U. S. Navy

Past Secretaries:

1889 P. A. Engineer R. S. GRIFFIN, U. S. Navy
1890 Assistant Engineer W. M. MCFARLAND, U. S. Navy
1891 Assistant Engineer EMIL THEISS, U. S. Navy
1892-93 P. A. Engineer W. M. MCFARLAND, U. S. Navy
1894-95 P. A. Engineer R. S. GRIFFIN, U. S. Navy
1896-97 P. A. Engineer F. C. BIEG, U. S. Navy
1898 P. A. Engineer W. M. MCFARLAND, U. S. Navy
1899 Chief Engineer A. B. WILLITS, U. S. Navy
1900 Lt. Comdr. A. B. WILLITS, U. S. Navy
1901 Lieutenant B. C. BRYAN, U. S. Navy
1902 Lieutenant C. W. DYSON, U. S. Navy
1903 Lt. Comdr. JOHN R. EDWARDS, U. S. Navy
1904 Lieutenant M. E. REED, U. S. Navy
1905 Lieutenant W. W. WHITE, U. S. Navy
1906 Lieutenant C. K. MALLORY, U. S. Navy
1907-08 Lt. Comdr. T. C. FENTON, U. S. Navy
1909-10 Lieutenant H. C. DINGER, U. S. Navy
1911 Commander U. T. HOLMES, U. S. Navy
1912 Lieutenant JOHN HALLIGAN, U. S. Navy; Lt. Comdr. E. L. BENNETT, U. S. Navy
1913 Lieutenant O. L. COX, U. S. Navy
1914 Lt. Comdr. H. C. DINGER, U. S. Navy
1915-16 Lieutenant A. T. CHURCH, U. S. Navy
1917 Lt. Comdr. J. O. RICHARDSON, U. S. Navy; Lt. Comdr. F. W. STERLING, U. S. Navy, Retired
1918 Lt. Comdr. F. W. STERLING, U. S. Navy, Retired
1919 Lt. Comdr. F. W. STERLING, U. S. Navy, Retired; Commander J. S. EVANS, U. S. Navy
1920 Commander J. S. EVANS, U. S. Navy
1921 Commander J. S. EVANS, U. S. Navy; Commander S. M. ROBINSON, U. S. Navy
1922-23 Commander S. M. ROBINSON, U. S. Navy
1924-25 Commander BRYSON BRUCE, U. S. Navy
1926 Commander A. M. CHARLTON, U. S. Navy
1927 Commander H. B. HIRD, U. S. Navy
1928 Commander H. B. HIRD, U. S. Navy; Captain O. L. COX, U. S. Navy
1929-30 Commander H. T. SMITH, U. S. Navy
1931 Captain O. L. COX, U. S. Navy
1932 Commander H. F. D. DAVIS, U. S. Navy
1933-34 Commander H. B. HIRD, U. S. Navy
1935 Commander C. S. GILLETTE, U. S. Navy
1936 Commander C. S. GILLETTE, U. S. Navy; Commander ROGER W. PAINE, U. S. Navy
1937 Commander ROGER W. PAINE, U. S. Navy
1938 Commander ROGER W. PAINE, U. S. Navy; Lt. Comdr. GUY CHADWICK, U. S. Navy
1939-40 Lt. Comdr. GUY CHADWICK, U. S. Navy
1940-44 Captain J. E. HAMILTON, U. S. Navy
1945 Commander R. T. SUTHERLAND, JR., U. S. Navy
1945-48 Captain F. W. WALTON, U. S. Navy